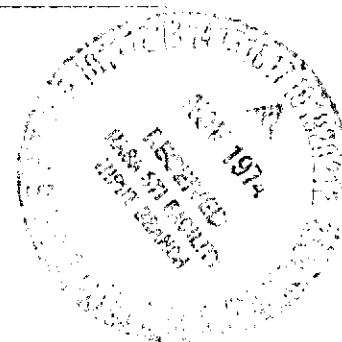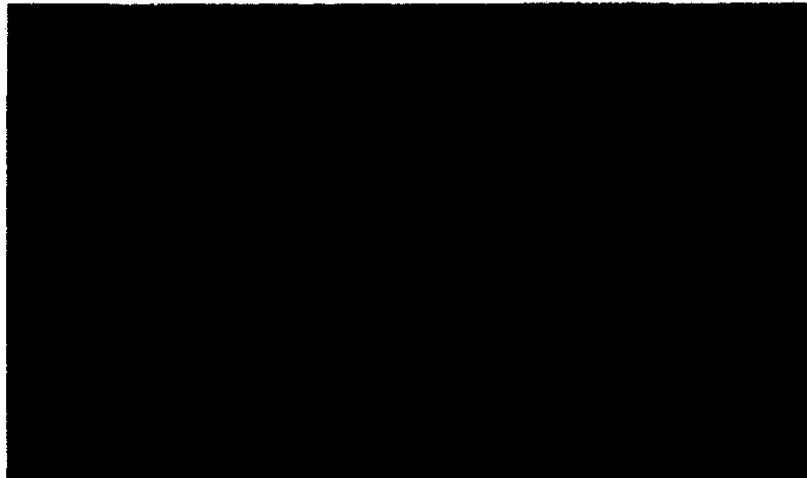# RESEARCH REPORT

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TECHNICAL REPORT

on

INTERACTION OF MARINE GEODESY, SATELLITE
TECHNOLOGY AND OCEAN PHYSICS

June, 1972

by

A. G. Mourad and D. M. J. Fubara

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FOREWORD

This report covers activities performed by Battelle's Columbus Laboratories (BCL) on behalf of the National Aeronautics and Space Administration, Wallops Station, under Contract No. NAS6-2006, "Services for Oceanography, Geodesy, and Related Areas Task Support". The NASA project monitor was Mr. H. R. Stanley. The Battelle program manager was Mr. A. G. Mourad.

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ABSTRACT

The objective of this study was to investigate the possible applications of satellite technology in marine geodesy and geodetic related ocean physics. Four major problems were identified in the areas of geodesy and ocean physics: (1) Geodetic positioning and control establishment; (2) Sea surface topography and geoid determination; (3) Geodetic applications to ocean physics; and (4) Ground truth establishment. It was found that satellite technology can play a major role in their solution. Furthermore, these problems are interrelated and solution of one offers new approaches in the others.

For solution of the first problem, existing satellite geodetic techniques such as Doppler and C-band radar ranging can be used to fix the three-dimensional coordinates of marine geodetic control if multi-satellite passes are used. In addition, the application of geodetic acoustic techniques will be required to relate accurately the ship-satellite-derived positions to the bottom control. The accuracy of such techniques needs to be determined under controlled-condition experiments. Furthermore, the development of advanced systems is necessary to provide the higher level of accuracy required for special operations. The second problem appears unresolvable with conventional techniques without the use of satellite altimetry. Solution of this problem will require accurate knowledge of ocean-dynamics parameters, such as sea state, ocean tides, and mean sea level, which also constitute topics of concern in solving the third problem. Solution of the third and fourth problems offers challenges to both marine geodesy and satellite technology, and it appears that use of both conventional and advanced satellite techniques will be required in their solution.

The various users' needs, the role of satellites, and the relevancy of marine geodesy to several national and international activities, were examined, and it was found that several practical problems, such as determination of boundaries at sea, can be established accurately only by application of geodetic techniques. Certain environmental ocean problems such as tides, mean sea level and ocean spreading will require very stringent accuracy for their solution which may be achieved only through application of advanced satellite and geodetic techniques.

Common to all these problems is an apparent unawareness of the applicability of satellite technology and geodetic techniques to their solutions and the nonexistence of a well-defined national program.

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TECHNICAL REPORT

on

INTERACTION OF MARINE GEODESY, SATELLITE
TECHNOLOGY AND OCEAN PHYSICS

to

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WALLOPS ISLAND, VIRGINIA

from

BATTELLE
Columbus Laboratories

by

A. G. Mourad and D. M. J. Fubara

June, 1972

1.0 INTRODUCTION

The success of NASA's Satellite Application Programs for
environmental quality control and prediction and for effective explor-
ation of marine resources will require advancements in marine geodesy
and accurate knowledge of the physics and dynamics of the oceans. The
study covered in this report has revealed how satellite technology
might best be used in the establishment of geodetic control and ground/
sea truth, in determination of an absolute global geoid, and in appli-
cation to ocean physics. This work, in conjunction with other NASA
work on satellite altimetry, will have far-reaching influence on ocean-
ography, and problems of the environment. Satellite altimetry will make
possible accurate determination of the geoid which is extremely important
for geodesy, oceanography, satellite orbital computation, space research,
and other scientific purposes, as well as for national defense.

The need for determining an absolute global geoid to better
than 1 meter accuracy has already been established (11,21)[*]. It has also
been found that conventional techniques cannot meet requirements within
reasonable time and costs. The use of satellite altimetry offers the best
potential for determining the required geoid. To evaluate the results of

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[*] References are shown beginning on page 86.

such an experiment, techniques must be developed for determining ground/
sea truth. Conventional techniques combined with the use of marine geodetic
control and sea-state information will be essential to provide the needed
ground/sea truth.

The scope of this study included the determination of the require-
ments for improved ocean geodesy, and the roles of satellite geodesy tech-
nology and related precision measurement techniques in meeting these
requirements. Thus, the program objective was to establish possible
applications of the techniques of satellite geodesy to support marine
geodesy for providing accurate geodetic control and geoidal information
for marine applications such as oceanography, navigation, geophysical
and geological explorations, defense weaponry, and instrumentation
calibration.

During this investigation, several problems were identified
in the areas of marine geodesy and ocean physics. In considering possible
solutions to these problems it was found that satellite technology can
make significant contributions. At present, there is a general unawareness
of the relevancy of satellite technology and marine geodesy to various
ocean interests and activities, of their practical applications to
environmental and scientific problems, and of the contributions they
can make to the solution of problems in ocean dynamics.

Unfortunately, unlike satellite geodesy on land, marine geodesy
has never achieved the status of having formal programs in the geodesy
discipline nor have the marine scientists in allied fields, from lack
of understanding, recognized the potential it has for solving their
problems. Thus, marine geodesy has not only been relegated to a
competitive role with marine sciences, but its merits and potentialities
have been ignored in existing geodetic programs which focus mainly on
land-related problems.

This report also describes the various users' needs, examines some of the basic problems of marine geodesy and ocean physics of importance to users and possible solutions, and the contribution of satellite technology in dealing with the growing problems of a social, legal, or economic nature associated with various ocean activities. On land, territorial boundaries have perhaps caused more international conflict and social litigation than any other single dispute. Such conflicts must be averted in the oceans where, already, territorial claims to fishing rights, mineral resources, and commercial navigation are engendering great concern. Geodetic control, accepted by all concerned, obviously is one answer. From the international point of view and for determination of claims in the deep ocean, satellite techniques combined with marine geodetic techniques offer potential and it is essential that these techniques be immediately considered and implemented.

The question of boundaries, surely to come up during the 1973 Geneva Law of Sea Conference, cannot be positively and permanently resolved without the use of marine geodetic capability and suitable technology for physical markation.

Review of available literature on this conference clearly indicates that the problem is being considered from the legal point of view alone, without practical considerations as to what constitute boundaries, how they can be established, and what accuracy or tolerance limits should be set. To simply state, for example, 200-meter isobath or 200 miles from a shore line as a boundary definition is not sufficient unless allowable tolerances of errors and how to precisely check them out are also stated. There is no such thing as "exactness" in physical measurements. It is insufficient to merely extend boundary lines on maps to a given distance from shore, for example, without establishing the physical representation through accurate measurement procedures. Such representations can be achieved through satellite technology and marine geodesy.

The four major problems of special interest in marine geodesy and ocean physics where satellite technology can be of use are:

(1) Establishment of geodetic control

(2) Determination of the geoid (mean sea level) in the oceans

(3) Geodetic applications to ocean physics

(4) Establishment of ground/sea truth.

Many of the details involved in the solution of these major problems are interrelated. For example, in theory, the required three-dimensional geodetic coordinates for establishment of geodetic control can be determined without knowledge of the geoid. In practice, this process at sea is dependent on satellite technology and inertial navigation which demand accurate knowledge of the earth's gravity field which currently is not well known. For earth gravity modeling and also for determining geodetic heights, mapping, and ocean-dynamics computation, an accurately defined geoid is needed. Conversely, for determination of the geoid, accurate knowledge of the three-dimensional coordinates of several points is required to provide the necessary scale information. Both control points and geoidal profiles in test areas will be required to establish the necessary ground/sea truth for geoid determination by satellite altimetry which appears to be more suitable than conventional techniques.

The solution of these problems requires accurate knowledge of certain factors associated with the dynamic ocean environment. The lack of such knowledge has limited the accuracy of geodetic measurements obtainable with conventional geodetic techniques. Examples are open-ocean tides, mean sea level, changing sea state, and underwater acoustic refraction. These constitute some of the ocean-physics problems of interest to marine geodesy. The recently developed geodetic acoustic techniques examined during this study offer a potential for solving several ocean-physics problems that are of major importance for understanding the environment. In addition, the use of marine geodetic control points offers practical applications in detailed surveying and mapping and in physical establishment of national and international boundaries. These are essential for effective and economic development of ocean resources and for improving international relations.

A requirement for solution of the four major problem areas is geodetic positioning capability for ships. Such capability was examined with respect to available satellite positioning systems and it was found that these systems could meet some, but not all, of the marine geodetic requirements. It was not possible within the limits of this study to determine definitely the accuracy achievable with such satellite systems at sea. Results in the literature are inconclusive and nowhere are they based on controlled-condition experiments. The lack of conclusive accuracy data is not unique to satellite positioning, however. Most of the other conventional positioning systems suffer from lack of an absolute "yard-stick" at sea against which systems' accuracies can be measured. Such a yardstick can be established, for example, by using marine geodetic control. For the establishment of such control yardsticks, the role of satellites was found to be essential, particularly in the open oceans.

The use of the existing Doppler satellite navigation system for determining the three coordinates of a ship's position is not possible from data obtained from only one satellite pass. Data from several satellite passes plus the use of ocean bottom acoustic transponders will make this possible. These transponders are essential not only for determining the third coordinate, but also for providing independent and accurate infor- mation on the ship's velocity, which is needed as an input for the Doppler obtained position.

Another satellite system that has been recently experimented with for ship positioning is the C-band radar ranging system. Although this system is not so much influenced by errors in ship velocity as the Doppler, no conclusive results are available as to its full potential in marine geodetic applications. The more advanced satellite systems that have been considered by DOD are expected to provide better accuracy in determining the three coordinates of moving vehicles. These systems have not been considered in this study. Very Long Baseline Interferometry (VLBI), a new concept which was considered, appears to have some potential for meeting the stringent accuracy requirements for position determination in both terrestrial and marine geodesy. The VLBI concept can operate with either natural radio sources or sources on artificial earth satellites.

The state of the art in satellite technology and marine geodesy has been advanced to a point where a coordinated, well-planned program will not only meet the requirements, but will also provide valuable practical and economic results. The basic component of such a program is described in Section 2 of this report. The results of this study corroborate Resolution No. 4 of the International Association of Geodesy of the International Union of Geodesy and Geophysics (Moscow, 1971) which recommends:

"1. that the following activities be encouraged:

    (a) the establishment of "marine test sites" or marine geodetic ranges suitable for the calibration and verification of precise measurement systems and methods,

    (b) the conduct of "controlled condition" experiments to determine the best accuracy attainable,

    (c) the publication of such results;

2. that studies be continued on methods of determining the form of the geoid by satellite altimetry taking oceanographic parameters into account;

3. that specific marine geodetic experiments be designed and conducted, and improved data analysis techniques be developed, to permit the determination of tides, mean sea level, ocean surface heights above mean sea level and sea floor spreading;

4. that the development of astronomic instruments useable at sea, capable of obtaining one second of arc or better in position determination, be encouraged to enable the geoid determination by astrogravimetric and astrosatellite techniques at sea."

This study is incomplete because the exact roles of satellite technology and marine geodesy in existing national and international activities have not yet been determined. Such roles will presumably be considered during the second phase of this research program. It appears, however, in the light of this study and on the basis of Battelle's present assessment of ocean problems, that satellite technology and marine geodesy can make a valuable contribution to many of these activities.

2. CONCLUSIONS AND RECOMMENDATIONS

2.0 General Conclusions

On the basis of this study, it appears that satellite technology offers outstanding capabilities that can play a significant role in meeting the marine geodetic requirements identified with accurate positioning, establishment of geodetic control, determination of an absolute global geoid and their applications to solution of oceanographic or ocean-physics problems. The use of geodetic control points from the application of marine geodetic techniques and satellite technology offers excellent potential for solving many problems in ocean physics and in special operations requiring the highest accuracy in their coordinate determination. There are many practical and scientific problems in the oceans that can be solved only by satellite and marine geodesy, such as establishment of international boundaries, establishment of ground truth for mean sea level determination and for positioning systems calibration and evaluations, and direct measurement of ocean-floor spreading.

Marine geodesy with the aid of satellite technology has a high degree of relevancy to certain national and international activities (see Section 5, Table 5.1). Of these, from practical and legal points of view, determination and identification of sea boundaries offer the biggest challenge to marine geodesy and satellite technology, particularly the establishment of international boundaries in the deep ocean areas. From the scientific point of view, direct measurement of ocean spreading, offers the biggest challenge. For improving our knowledge of the environment and its monitoring, measurements of ocean tides and mean sea level and the adaptation of the techniques involved to tsunami detection are the most challenging. From the economic point of view, marine geodesy and satellite technology offer unlimited applications for both surveying and mapping and for development of ocean resources.

For all practical purposes, the stringent accuracy requirements for various operations, as shown in Table 3.1 (Section 3), are unlikely to be satisfied without the use of satellites and geodetic control. With advanced satellite systems capable of much higher position accuracy than offered by the present satellite systems, geodetic control will still be required at least for the evaluation of the capability of such advanced systems.

From a comparison of various marine geoids as determined by
conventional techniques and satellite altimetry (see Section 4, Table 4.1),
it was concluded that satellite altimetry offers the best potential for
determining an absolute global geoid. Astrogravimetric techniques as well
as satellite C-band radar ranging techniques offer the best means for
determining absolute geoidal profiles to be used as sea truth for evalu-
ation of satellite altimetry data.

2.1   Specific Conclusions

The specific conclusions of the study are given below. Most
important, however, is that most of the identified needs cannot be met
without the use of advanced satellite technology.

2.1.1   Establishment of Geodetic Control at Sea

(1)   A need exists for establishment of geodetic control
points on the ocean floor for specialized operations
requiring a high degree of accuracy, such as determi-
nation and identification of boundaries, location of
mid-ocean satellite tracking stations, establishment
of ground truth in support of satellite altimetry,
measurement of ocean tides, and determination of
sea-floor spreading and mean sea level. These points
must be established with an absolute accuracy better
than ±10 m (compatible with land control) in the
horizontal coordinates and ±0.5 m in the vertical
coordinate and referenced to a global geodetic system;
gravity values should be determined at these stations
to an accuracy of 0.1 mgal, magnetic dip to ±1', and
magnetic intensity to ±1 gamma.

(2)   Basic positioning requirements identified in the 1968
Battelle study for NASA have not significantly changed (108).
However, there has been a significant change in the attitude
of oceanographers and other potential users of satellite
technology; whereas in 1968 there was skepticism as to
their potential, in 1971 there is eagerness to use satellite
data and equipment. This change is believed to be due to
acquired knowledge or experience in Doppler satellite use
and applications.

(3) There are practical and political problems associated
with the use of satellites for positioning in surveying and
mapping. For example, the incompatibility of satellite-
derived coordinates (geocentric) and existing various map
coordinate systems referenced to national datums must be
resolved in order to make land and ocean maps compatible.
The use of control points would resolve this problem.

(4) A need continues to exist for accurate worldwide position
capability and it appears that satellites will offer the
best potential for meeting such requirements. The present
Doppler satellite navigation system cannot meet many of the
stringent accuracy requirements of marine geodesy (shown
in Table 3.1). This system, for example, cannot determine
the three coordinates of a ship from a single satellite pass.
The use of several passes with marine geodetic control will
make it possible to determine the three coordinates. Actual
orbital data (not predicted) and accurate ship velocity
information are required to improve the accuracy of positions

(5) Similarly, ranging data to geostationary satellites alone
cannot provide accurate three-dimensional coordinates.

(6) Diverse approaches are being considered and used for the
solution of positioning problems at sea--mostly "piecemeal"
with no systematic evaluation of equipment used, data acquired,
and results obtained. Information in the technical liter-
ature is insufficient for comparison purposes--there is
ambiguity and inconsistency in the reporting of results.

(7) The absence of reliable and consistent procedures for
determining the accuracy of position fix at sea, both from
satellite and conventional means, even at present, continues
to be a major problem facing designers of new equipment and
management decision makers. This problem is perhaps more
pronounced with satellites, particularly in the deep ocean,
because of the limited systems available for comparison.

(8) Accurate ship-velocity information to better than 0.1 knot (5 cm/sec) is required for certain operations, such as gravity measurements for geophysical explorations as well as for defining more reliable earth gravity models.

(9) A need exists for establishment of a test area and for conducting "controlled-condition" experiments to assess accuracies. Use of a suitably equipped ship over an array of ocean-bottom transponders is required for determining ship velocity, establishing the three-dimensional coordinates from multiple satellite passes, and for statistical analysis of data. It is desirable that experiments be conducted in the deep water within 100 miles from shore to permit use of two independent surface electronic positioning systems, accurately tied into terrestrial geodetic datum for assessing satellite position fix at sea under varying conditions.

(10) A need exists for studies of the best surveying and acoustic ranging patterns for reliable location of ocean-bottom markers relative to surface-ship positions.

(11) A need exists for efficient and improved bottom markers and sound velocity-profiling-hardware.

2.1.2 Techniques for Geodetic Control at Sea

There are two basic categories of techniques available for determination of accurate geodetic controls at sea.

(1) Techniques suitable for relating ocean-surface measurements to the ocean bottom--the most commonly used technique is the line-crossing technique. It is limited in accuracy, depends on accurate knowledge of ship speed and heading, and makes invalid assumptions with respect to depth. To eliminate the shortcomings of line crossing, three new techniques have been developed and used at Battelle and are capable of obtaining ±3 m relative precision. Such precisions offer potential for applications of marine geodesy and satellite technology to solution of ocean physics problems, ship tracking, establishment of geodetic control, and for determination of national and international boundaries.

(2) Techniques suitable for determining absolute or relative geodetic coordinates of surface positions--the most commonly used techniques are the surface-based electronic positioning systems which are reportedly capable of high precision but are limited in range. Their precision decreases as the distance from shore increases. Examples of these systems are LORAC, Raydist, Hi-Fix, autotape, and LORAN. The airborne techniques can be used for independent distance measurement of geodetic networks. However, only the LORAC line crossing technique has been experimented with at sea successfully. Other techniques available are satellites such as Doppler and C-band radar ranging. These offer an important advantage over surface-based and airborne techniques in that they can be used on a worldwide basis. No conclusive results on their absolute accuracy are available in the literature. There are future advanced techniques being considered such as VLBI, laser ranging, Unified S-Band, DOD satellite systems (Timation, 621-B, and advanced Doppler). Except for VLBI, these systems have not been examined in this study. The VLBI, using natural radio or satellite sources appears to have a potential for meeting the stringent marine geodesy accuracy requirements if current theoretical estimates are realized in practice.

2.1.3 Geoid Determination at Sea

(1) A need exists for accurate determination of the mean sea level (geoid). With ±1 to ±2 meter accuracy, most of present geodetic needs are met; a better than 1 meter accuracy will be required for solution of many ocean-physics problems.

(2) Existing methods for determination of the geoid have several limitations and are inadequate for providing a global absolute geoid to meet the above accuracy requirements speedily and economically.

(3) Future planned methods such as satellite to satellite tracking and drag-free satellite could improve on the existing satellite-determined geoid, but they will still be accuracy limited.

(4) Satellite altimetry offers the best potential for providing an absolute global geoid to meet the above requirements.

(5) Several problems related to calibration, evaluation, and successful application of altimetry were identified.

(6) Astrogravimetric techniques and satellite ranging techniques, combined with marine geodetic control, offer the best means for determining absolute geoidal profile suitable for establishing ground truth in support of satellite altimetry. These techniques should be studied in detail and evaluated soon.

(7) Successful application of marine geodetic techniques and satellite altimetry to determine the geoid will enhance the accuracy of satellite tracking and orbital computation. These techniques will also make it possible to use tracking ships, such as the VANGUARD, for their original intended use.

2.1.4 Ocean Physics Applications

(1) Marine geodetic acoustic techniques for relating ocean-surface measurements to the ocean bottom offer significant potential for solving several classical ocean-physics problems, such as determination of open-ocean tides, mean sea level, sea-state, and ocean-floor spreading.

(2) Certain ocean-physics problems which were studied in isolation from the point of view of geodesists, oceanographers, or geophysicists, resulted in differing values that cannot be reconciled, e.g., mean sea level.

(3) There is a need for geodetic-parameter studies of several ocean-physics problems to define interrelationships between geodesy and ocean dynamics.

(4) A need exists for determining ocean tides, distinct from crustal earth tides.

(5) Present methods of determining ocean-floor spreading are indirect, but marine geodetic and satellite techniques have potential for direct determination of ocean-floor spreading.

2.2 Recommendations

The recommendations made here are based not only on this study but also on past experience regarding user requirements and overall identified needs for an orderly development and use of ocean resources and environment. One of the main recommendations is that a National Marine Geodetic Program with improved associated satellite technology should be established as a logical extension of the National Geodetic Satellite Program (NGSP). NASA played a direct leadership role in NGSP and because of the international implications and the need for satellites that can give the desired worldwide coverage, it is equally logical that NASA should assume leadership in the application of satellite technology for establishing a marine geodesy program in collaboration with other Government agencies. Such a program is highly relevant for: (1) oceanographic computations required for environmental quality control and prediction; (2) geodesy and mapping required for navigation, territorial boundary determination, resources development on land and at sea, and national defense; and (3) earth gravity model for orbit computation, space research, and evaluation of satellite altimetry.

A formal program in marine geodesy should be established where geodesists, oceanographers, other marine scientists, and space scientists could work as a team to reconcile and study problems and parameters involved. The practical and scientific elements of such a program should include improvement and/or development of suitable methods for:

(1) Establishment of primary geodetic control at sea for boundary determination, control of surveying and mapping, and for geodetic and ocean physics applications. The needed research includes:

   a. Determination of the absolute accuracy capability of positioning-systems hardware and software techniques

   b. Establishment of criteria and optimum survey patterns

   c. Improvement of analytical methods to be compatible with hardware precision

   d. Design and conducting of controlled-condition experiments for evaluation of satellite systems,

ship instrumentation, ground/air supporting
equipment, sound-velocity profiles, and ocean-
bottom equipment

e. Development of suitable advanced techniques.

(2) Determination of the geoid at sea. The research areas include:

    a. Development of methods and determination of para-
meters for satellite altimeter-instrument calibration

    b. Establishment of control geoidal profiles to provide
the necessary ground/sea truth, scale, and orienta-
tion for the satellite altimetry geoid

    c. Establishment of special-purpose satellite tracking
and orbit computation suitable for satellite altimetry

    d. Development of mathematical models for determination
of the geoid from satellite altimetry data.

(3) Applications to ocean physics. Examples of specific ocean-
physics areas are determination of open-ocean tides and mean
sea level, direct measurement of ocean-floor spreading,
and monitoring of the motion of ice sheets. The required
research should include:

    a. Studies of geodetic parameters of ocean-physics
problems to define interrelationship between
geodesy and ocean physics

    b. Development of suitable combined satellite and
other techniques for solution of these problems

    c. Conduct of special experiments for verification

    d. Development of satellite techniques for global
sea-state monitoring by altimetry and bistatic
radar Bragg scatter.

(4) Establishment of ground/sea truth in support of geodetic
position determination, geoid determination by altimetry,
and ocean-physics applications. The needed research includes:

a. Selection of suitable test areas

b. Preanalysis of experimental design (geometry, mathe-
    matical models, parameters, available hardware and
    facilities, tracking, etc.)

c. Design and conduct of controlled condition
    experiments in these areas

d. Development of evaluation criteria and establish-
    ment of marine geodetic standards for systems-
    capabilities evaluation

e. Establishment of absolute geoidal profiles.

3.0 PROBLEMS IN MARINE GEODESY AND OCEAN PHYSICS

Problems in marine geodesy related to ocean-physics phenomena and satellite-technology applications can be broadly classified under such headings as (1) geodetic positioning and control points, (2) determination of the geoid, (3) geodetic - ocean physics, and (4) establishment of ground truth.

3.1 Geodetic Positioning and Control Points

Geodetic positioning is the process whereby any chosen point is assigned a set of three-dimensional geodetic coordinates referenced to a predefined geodetic datum. Conventionally, the coordinates are given either by a set of curvilinear coordinates, geodetic latitude, (φ), longitude (λ), and ellipsoidal height (h), or a set of space rectangular Cartesian X, Y, Z coordinates. In each case, the mean rotation axis and mean terrestrial equator of the earth are the primary reference axis and plane, respectively. The well-known interrelationships between the curvilinear and Cartesian coordinates are expressed as:

$$X = (M + h) \cos \varphi \cos \lambda \qquad (3.1)$$

$$Y = (M + h) \cos \varphi \sin \lambda \qquad (3.2)$$

$$Z = \left[M(1 - e^2) \right] + h \ \sin \varphi \qquad (3.3)$$

and
$$M = a(1 - e^2 \sin^2 \varphi)^{-1/2}, \qquad (3.4)$$

where

  a = semimajor axis of the reference ellipsoid
      used in defining the geodetic datum

  e = 1st eccentricity of the reference ellipsoid

  h = the algebraic sum of the points heights above
      mean sea level (the geoid) and the geoidal
      height (undulation) above the reference
      ellipsoid at that point.

As in the case of terrestrial geodetic control, at sea any "permanently" marked station whose geodetic position is determined is a geodetic control point.

The above-stated interrelationships will be used to express the interactions between satellite technology, marine geodesy and certain aspects of ocean physics. Currently, ocean-bottom-mounted acoustic transponders or hydrophones are exclusively used to permanently mark marine geodetic control.

The determination of the three-dimensional coordinates of geodetic control at sea involves the solution of two problems: (1) determination of the geodetic positions of the survey ship, and (2) accurate location of ocean bottom markers with respect to ocean surface positions of the survey ship or platform. Most of the geodetic techniques developed for land use, including satellite geodesy, can be applied to the solution of the first problem as will be shown later. However, if accuracies of the order of a few meters are to be achieved in determining geodetic controls at sea (comparable to those on land), high-precision techniques must be developed for solving the second problem. Accordingly, much recent research has concentrated on the development and evaluation of such techniques.

3.1.1 User Needs and Accuracy Requirements

The first step in any organized and systematic development, exploration and exploitation and toward efficient, nondestructive management of any environment on land and even on the moon has always been accurate mapping and charting. Such mapping and charting are preceeded by systematic establishment of geodetic controls. As man's attention is turned to oceans in anticipation of finding the next generation of resources to sustain mankind and its civilization, it is only appropriate that the same proven methods for exploiting and managing the terra firma be extended to the oceans.

Terrestrial and space "geodetic mapping" include not only the determination of geometric coordinates, but also the environment dynamic and physical characteristics such as the gravity field, magnetic field, etc. Therefore, marine geodetic control points are needed to serve as

sites in the open sea for mapping control, for the calibration of positioning and surveying systems, and for navigation. It is desirable that these reference points be located in a unified worldwide geodetic coordinate system and that standards of gravity be known at each station to ± 0.1 mgal, magnetic dip to $\pm 1'$, magnetic intensity to ± 1 gamma, and water depth to ± 0.5 m (referred to mean sea level). It has been shown that such reference points can be marked by an acoustic-transponder array on the sea floor(1,9,11,113). It is desirable that these control points be used to record ocean tides.

Gravity measurements on a worldwide basis are needed to further the understanding of the earth's figure (size and shape) and mass distribution. The largest errors in gravity measurements at sea, whether the measurements were obtained from shipboard or airborne systems, are caused by navigational uncertainties. It is necessary that the E-W component of velocity of the surveying vehicle be known to 0.1 knot (5 cm/sec) for reduction of observed gravity with an accuracy of 1 mgal. Although, in the future, the successfull operation of satellite altimetry could eliminate the need for geodetic ocean gravity measurements, the initial steps to calibrate and validate satellite altimetry results need accurate gravity measurements.

The open-ocean reference points would be valuable in this connection for navigational control by serving as standard for calibrating navigation equipment and resetting navigation systems such as the inertial that require regular resetting. Using acoustic techniques for positioning relative to these stations could fill in the gaps between satellite fixes and would thus provide a much needed improvement in the measurement of ship velocity for the control and reduction of gravity observations (108,109).

The establishment of marine geodetic controls and the hardware and software techniques employed will be shown to be critical in the solution of several problems in (1) environmental monitoring, prediction and preservation - tides, air/sea interaction, ocean currents, ocean circulation, mass transport and their effects on waste disposal and pollution control and sea-floor spreading; (2) resources exploitation - mineral exploration and drilling, fishing and marine life farming; (3) national and international areas - defense, navigation, accurate boundary determination, and marine geodetic and navigation equipment calibration; (4) space and scientific research areas - earth gravity model, the figure of the earth,

satellite-orbit computations, and precise spacecraft tracking and guidance
from ocean stations. Table 3.1 is a summary of the position accuracy
requirements in terms of desired relative and absolute coordinates for
some of these problems.

Yesteryear, the world was insensitive to the need for pollution
studies and control, apparently unaware of the encroaching, possibly
irreversible, ecological damage. Systematic effort to preserve the
environment was absent. Today, these unattended problems threaten man and
are now costly to combat. Before long, the need at sea for physical
demarcation of international national and lease boundaries, and positive
re-identification of defined boundaries will become critical in averting
international and industrial friction. Territorial boundaries on land
have caused more international conflicts and social litigations than any
other single dispute. This situation must be averted in the oceans where
already territorial claims to fishing rights and commercial navigation
are raising serious concerns (90,122). Geodetic controls accepted by all
concerned may be the only answer.

The oceans are vast and so their systematic control and mapping
and studies to understand ocean dynamics may appear as remote or of low
order priority. Ocean exploration and exploitation are conducted piecemeal.
Scramble for ownership of definite portions of the oceans or international
control of uses of definite portions seem to be remote or improbable events.
Formalized hardware and software required for systematic ocean studies
and control are rudimentary. Intensive ocean dynamics knowledge and mapping
will be needed. Satellite technology appears destined to play the major role.
At the base of it all will lie requirements that only marine geodesy can
fulfill. Now is the time to gradually implement well-directed plans for
advancement of satellite technology for marine geodesy and ocean physics.

3.1.2 Problems in Establishment of Geodetic Controls

The two main problems in the establishment of marine geodetic
controls are:
(a) Geodetic Positioning of Ships. The various techniques in common
   use are described in Section 4.1. The major common problems are
   (1) the unknown absolute accuracy with which any of the techniques

TABLE 3.1. POSITIONAL ACCURACY REQUIREMENTS

Marine Activities	Desired Relative Accuracy (m)			Desired Absolute Accuracy (m)		
	φ	λ	H	φ	λ	H
Geodetic Operations						
Control points	1	1	1	10	10	5
Geoid	--	--	0.1	--	--	0.5
Calibration standards	1	1	0.3	10	10	5
Gravity base stations	10	10	1	10	10	5
Ocean Physics & Oceanography						
Mean sea level	--	--	--	50-100	50-100	0.1
Tides	--	--	--	50-100	50-100	0.1
Ice sheet motion	1-5	1-5	--	--	--	--
Stationary buoys location	10	10	--	10	10	--
Drifting buoys location	50-100	50-100	--	50-100	50-100	--
Ocean Tracking Stations	--	--	--	10	10	5
Search & Rescue & Salvage	1-10	1-10	--	20-100	20-100	--
Ocean Resources						
Geophysical surveys	10-100	10-100	5	--	--	--
Drilling	1-5	1-5	1-5	--	--	--
Pipelines	1-10	1-10	--	--	--	--
Cable laying	1-10	1-10	--	--	--	--
Dredging	2-10	2-10	--	--	--	--

can define a geodetic position relative to a stipulated geodetic datum, (2) elemination of systematic errors due to hardware calibration and the effects of the physics of the environment; (3) the lag in improvement of reduction, numerical, and statistical analysis of hybrid data to match advancement in technology (62). Inaccuracies in satellite emphemeris due to poor worldwide tracking coverage, errors in earth gravity models, and uncertainties in the absolute positions of tracking stations limit the degree of accuracy obtainable from geodetic positioning by satellites. The determination of three-dimensional geodetic positions as defined earlier, requires the use of multipass satellite data for each station. Ship relative positions, heading, and speed during each satellite pass and in between successive passes must be accurately accounted for.

(b)   Ocean Bottom Markers Relative to Survey Ship Positions. Most of the commonly used techniques are described in Section 4.2. Inaccuracy of the knowledge of the exact sound-velocity profile prevalent at the time of survey measurements is the biggest limiting factor on the "absolute" accuracy of relating ocean-bottom markers to surface-ship positions. With techniques using a curvilinear or horizon coordinate system as in Reference (60), the influence of inaccurate sound-velocity profile in establishing the two horizontal coordinates can be eliminated. On the vertical coordinate, this error source acts as an incorrect scale factor.

3.2   Geoid Determination at Sea

The geoid is that equipotential surface in the gravity field of the earth which most nearly coincides with the undisturbed mean sea level. In spite of this exactness of definition, the physical determination of the true geoid remains an elusive target to geodesists. Consequently, many concepts and classes of concepts for physically determining the geoid have been advanced (61). In scale, shape, and orientation, each class of geoids has little in common with another class. Even within the class, the various geoids differ and depend on many factors, such as (1) the parameters of the reference ellipsoid which, for convenience, geodesists

always associate with each geoid; (2) the measuring technique, the measurements, and their reductions in theory and in practice, (3) the quantity and quality of data, and (4) the datum origin of the geodetic system.

Because the geoid is an irregular figure, it is geometrically defined by its physical departures (geoidal undulations) from a chosen regular figure which is usually a reference ellipsoid. In some methods, the departures are determined by linear and angular measurements, while in others these departures are synthesized from gravity anomalies integrated all over the earth's surface or a combination of both. The latest generation of geoids is deduced from the analysis of the dynamics of satellite orbits or a combination of gravimetry and satellite-orbit analysis. Future plans are to measure ocean surface topography from satellite altimetry and hence deduce the geoid with a correct absolute orientation, scale, and shape. A broad classification of the various geoids and their compatibility with the expected satellite altimetry geoid is shown in Table 3.2.

3.2.1 User Needs and Accuracy Requirements

There is a need to determine the geoid accurately because it is a mandatory parameter in the solution of certain problems in geodesy, satellite-orbit computation, oceanography, marine environmental-quality monitoring, prediction and control, marine-resources exploitation, navigation, and national defense.

Accurate determination of the geoid is needed to determine the figure of the earth and its gravity field. The figure of the earth must be known to establish systematic and accurate geodetic controls which are needed for systematic and accurate mapping. The role of mapping and physical demarkation of boundaries in environmental development, exploitation, and management of resources has been discussed earlier. Worldwide mapping, accurate geodetic controls, and definition of the earth's gravity field are indispensable to national defense needs and resolution of international boundary conflicts. No matter what the extent of technological advancement, navigation can scarcely improve without accurate determination of the figure of the earth, establishment of geodetic controls, and development of reliable maps.

| Type of Geoid | Compatibility Criteria | | | Quality of Geoid and Sources of Deficiencies |
	Absolute Orientation	Correct Scale	True Shape	
(1) Astrogeodetic (classical)	No	Yes	False tilt	Detailed local geoid highly dependent on density and accuracy of deflection stations. Rapid error accumulation. Bad local datum influence. Currently not expedient at sea. Not compatible.
(2) Astrosatellite	Yes/No	Yes	Possible	Currently poor accuracy at sea as geoid _details_ need highly accurate and dense data distribution. Suitable for evaluation but not absolute calibration of Sat. Alt. "Geoid".
(3) Inertial	No	Not reliable	Not reliable	Very poor accuracy, deficiencies in theory for data deduction. Accurate external geodetic reference required in navigation mode. Not compatible with Sat. Alt. "Geoid".
(4) Gravimetric (a) Stokes'	Yes	<u>No</u>	Possible	Not for ABSOLUTE CALIBRATION but good for shape evaluation. Needs adequate global coverage of data; theory problems in data prediction and reduction. Compatible in shape and orientation only but not in scale.
(b) Vening Meinesz	Yes	Possible dependent on initial point	Possible	More dependent on dense local gravity net and less influenced by distant zone data which are still needed. Problems in prediction and reduction theories. Compatible in shape and orientation but correctness of scale dependent on assumed initial point.
(5) Satellite (a) Geopotential coefficients	Yes	Dependent on method used	General outline	Poor coefficient accuracy, inadequate for geoid details. Not suitable for calibration of Sat. Alt. "Geoid".
(b) Geometric/ dynamic	Possible	Yes	Possible	Highly dependent on orbit accuracy and geometry. Could provide in the future compatible detailed geoid profiles.
(6) Combined Satellite/ Terrestrial, Astronomic, Geodetic, Gravity	Yes?	Yes?	Yes?	Development of techniques in progress. Theoretically, could provide global geoid using <u>world-wide data</u> coverage. Not suitable for local geoid details as required for satellite altimetry test areas.
(7) Astrogravimetry	Yes	Yes	Yes	Requires ONLY LOCAL GRAVITY data, speedy and economical. BEST suitable for geoid details in Test Areas. COMPATIBLE with expected Sat. Alt. "Geoid" in scale, shape, and orientation.
(8) Satellite Altimetry	Yes	Yes	Yes	Development in progress. If successful, provides the best hope currently for speedy, economical determination of global marine geoid with sufficient accuracy and details to meet oceanographic, geodetic, space programs, environmental control and prediction needs.

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One of the greatest unresolved problems limiting the accuracy of satellite orbit computations is the lack of an accurate earth gravity model. The plans to experiment with satellite-to-satellite tracking, drag-free satellites, and "Cannon" ball satellites as means of better determination of the earth's gravity model emphasize the urgent need for improved definition of the earth's gravity field. This problem would be resolved if the geoid in its true scale, shape, and orientation were known accurately. The planned satellite altimetry missions on Skylab and GEOS-C are designed to meet this need. For all the above purposes, a determination of the geoid to within ±1 m accuracy is satisfactory.

Oceanographers indicate an urgent need to determine the geoid with an accuracy of ±10 cm or better. This is a requirement for investigating ocean currents, ocean circulation, and mass transport that affect air-sea interaction information needed for reliable weather forecasts, waste disposal, and pollution-control efforts (11,151).

From the definition of the geoid, its true center must coincide with the earth's center of mass and its rotational axis must coincide with the earth's mean rotational axis. This implies that the orientation of the geoid determined to meet the above needs must be absolute and has the shape and scale to make it coincident with undisturbed global mean sea level. The problem and remedies associated with these requirements are discussed by several authors (21,61,86). Kaula (86) presents an excellent exposition on the needs for the geoid, the roles of satellites technology, the views of the National Academy of Sciences on "Priorities for Space Research 1971 - 1980", (19) and the tremendous practical benefits mankind can derive from solving the problems of geodesy and ocean physics.

3.2.2 Problems in the Determination of the Geoid

The core of the problem in geoid determination is to design a speedy and economical way to determine the geoid that has correct orientation, shape, and scale. All conventional nonsatellite techniques for

the gravity method, the cost of measuring gravity over the entire earth's surface (both land and oceans) accurately and in sufficient quantity is substantial enough that no such program is being undertaken systematically. Even if such a program were initiated and funded, the completion time frame is of the order of 10 years or more. Besides, political and national-defense interest may not currently permit a unified worldwide measurement of gravity. Above all, such a program lacks the public participation and charisma to get it funded. The second major problem, as shown in Table 3.2, is that none of the existing conventional techniques, except astro-gravimetry (61,71,103) are capable of determining the geoid in its correct scale, shape, and orientation.

To combat these problems in the oceans is one of the main purposes of the satellite altimetry missions. However, the achievement of satellite altimetry objectives depends on, among other things, the accurate determination of segments of the geoid in test areas by conventional means. The other associated problems include satellite-tracking and - orbit determination, sea-state measurements, and hardware calibration (21).

3.3 Geodetic - Ocean Physics

There are many ocean-physics phenomena that are either implicit in the solution of geodetic problems or are themselves resolvable by the application of geodetic techniques. Such phenomena include ocean tides, mean sea level, sea state, tsunami, sea-floor spreading, ocean circulation, ice-sheet motion, etc.

3.3.1 User Needs and Requirements

By definition, undisturbed mean sea level (msl) is the geoid. There-fore, the needs and requirements for the determination of msl are the same as elaborated for the geoid in Section 3.2.1. Spirit leveling remains the most precise technique for terrestrial determination of relative heights. Spirit leveling is basically measurement of seperation of the gravity field equipotential surfaces at the various points concerned. The datum or zero surface to which these height measurements are referred is the msl or geoid.

Accurate height determination is indispensable for many engineering, and scientific operations such as navigation and air fields relative positions, construction of dams, man-made waterways and drainage control; and geodetic and geophysical monitoring of earthquake and tectonically unstable regions. Most of these operations call for millimeter accuracy. The reference datum, msl, is determined by tide gage recordings of tides averaged over several years, commonly not less than 11 years.

This brief discussion and the previously outlined needs of geodesy and oceanography for determination of msl emphasize the need to measure tides not only at coastal stations but also in the deep oceans. To explore and exploit the oceans efficiently and safely, monitor ocean-associated environmental hazards, and preserve the environment, the dynamics of the oceans must be understood. Ocean tide (currently ill-known) measurement and determination of mean sea level (geoid) are fundamental to accurate modelling of the complex ocean environment because it will resolve problems concerning (1) locating cotidal lines, tidal co-range lines, and amphidromic points, and (2) energey dissipation mechanism and patterns, ocean currents, circulation, and mass transport which affect fisheries, waste disposal and pollution control, air-sea interaction that affects weather forecasting to protect marine and air navigation and human lives on the continents.

Tsunamis are devastating marine phenomena believed to be generated by earthquakes. Their prediction is still a major problem. Sea-state knowledge is important for safety in marine navigation, accurate weather forecasts, and coastal management. Accurate measurement of sea-floor spreading is a key factor in understanding the tectonics of the earth's outer rigid crust and the activities of the earth's mantle. Currently, seafloor spreading and plate tectonics are simply inferred from marine magnetic anomaly patterns. The applications of satellite and marine geodetic techniques to the solution of these problems are discussed in Section 5.

3.3.2 Discrepancies in Geodetic and Oceanographic Determination of Mean Sea Level

The brief discussions above put in its true perspective the

importance of determining "ocean tides", which must be separated from the
influences of "earth tides". Because the earth's crust is not a perfectly
rigid body, its elastic response to the attraction forces of the moon and
sun is the phenomenon termed earth tide, which perhaps should have been
termed "crustal tide". The corresponding response of the fluid oceans
results in oceanic tides. The tide observed with tide gages is the
difference between the ocean tide and that of the crust to which the
tide gages are attached. This is a simplified account of highly complex
phenomena that are well treated by many authors (101, 120, 159-162).

Theoretically, the combined lunisolar effects should give a
maximum oscillation of 78 cm for the geoid or mean sea level if the
earth were a perfect liquid not affected by any other dynamic forces.
An infinitely rigid earth would of course undergo no deformations or
exhibit tides. The variable "elasticity" of the solid earth and the
fluid oceans, the influences of coastal and ocean-bottom topography,
variability in the thermal structures of the oceans, atmospheric inter-
action, and other dynamic forces all combine causing measured tides to
have variable amplitudes with time and place.

Mean sea level, or the geoid, as determined from averaged
values of a tide gage records at any terrestrial station can be
connected to that of another station by precise geodetic spirit leveling.
In theory, and exclusive of systematic observational and instrumental
errors, the result of such a leveling line connection should show a zero
height difference between mean-sea-level marks at all coastal stations.
In practice, such precise leveling results in the U.S. indicate that msl
appears to rise from south to north on the Atlantic as well as on the
Pacific coast (143,72). According to Braaten and McCombs (35), on either coast
the rise is approximately 60 cm, but actually msl along the Pacific coast
is, on the average, about 60 cm higher than on the Atlantic coast, as
shown in Figure 3.1

There are oceanographic computations which supposedly could
duplicate and check the geodetic leveling results. The oceanographic
leveling is based on the assumption of a reference level which cannot be
physically defined nor be experimentally proven. There is no valid mechanism
to relate at different parts of the same ocean or between any two oceans
the arbitrarily assumed oceanographic reference levels. Nevertheless,
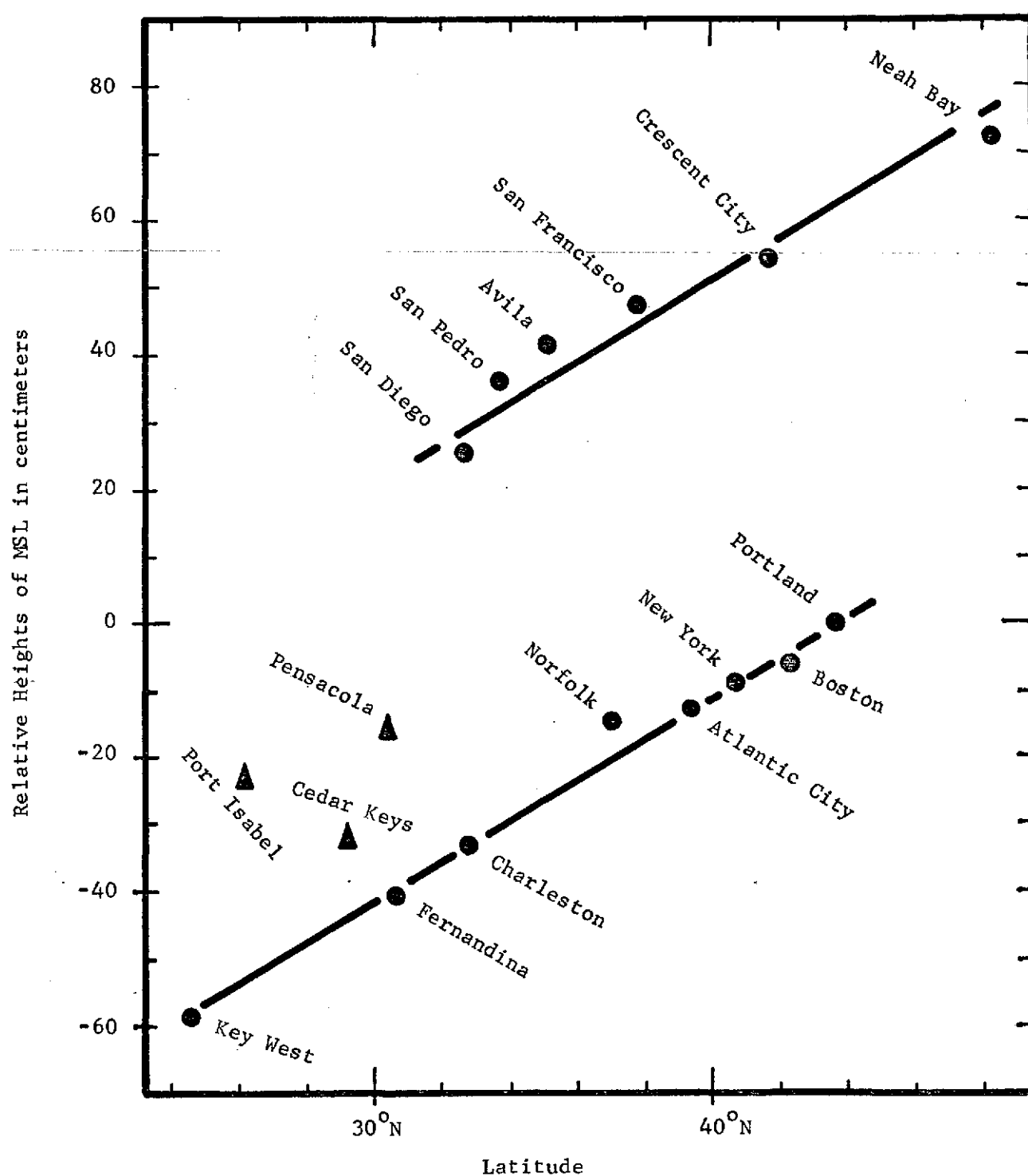
FIGURE 3.1   RELATIVE HEIGHTS OF MEAN SEA LEVEL VERSUS LATITUDE BASED
ON THE SPECIAL LEVELING ADJUSTMENT OF 1963 (After Braaten
and McCombs 1963). ATLANTIC AND PACIFIC COAST TIDAL
STATIONS ARE SHOWN BY DOTS; GULF-COAST STATIONS BY TRI-
ANGLES. THE LINES HAVE SLOPE 0.28×10^{-6}. VERTICAL
EXAGGERATION IS APPROXIMATELY 2×10^{6}.(142)

Montgomery (104) concluded that the oceanographic-leveling and geodetic-leveling results agree on the approximate differences in msl between the Pacific and Atlantic coasts of the U.S. However, according to Sturges (142), oceanographic results disagree with the geodetic results on the issue of the rise of 60 cm. of msl from south to north on either coast of the U.S. The oceanographic results show, instead, a fall in msl of 9 cm. from south to north on the U.S. Pacific coast.

This issue is very important because of the oceanographic need to separate the slopes of ocean surface topography from that of the geoid. This is a key factor in most physical oceanography computations for important phenomena such as ocean currents, ocean circulation patterns, mass transport, and energy dissipation. The importance of solving these problems has been repeatedly emphasized because their solution is vital to man's future existence in comfort (86,140,150,151).

The successful implementation of a satellite altimetry program and measurement of ocean tides in combination with coastal tide gages and geodetic leveling, should resolve the discrepancies and furnish the oceanographers a realistic and definable reference level.

The geodetic techniques are theoretically flawless, and the measurements are repeatable under varying conditions, instruments, and personnel. They have built-in constraints to isolate measurement blunders and instrumental systematic errors. However, they are vulnerable to environmental factors such as atmospheric refraction, solid-earth and ocean tides, and other variable dynamic forces within and outside the earth. Inadequate corrections for the influences of these phenomena contribute errors whose exact nature is not well known. Refraction correction errors are usually systematic and perhaps may have cumulative effects northwards and southwards from the equator along any coast because of systematic temperature, atmospheric, and climatic changes and the sun's angles. Solid-earth and ocean tides produce periodic systematic effects on high-precision geodetic leveling (101). These periodic deformations of the level surfaces and of the geoid in particular, the small variations of the intensity of gravity and direction of local vertical, tidal caused variations in the largest moment of inertia of the earth and the resultant change in its speed of rotation, the radial distribution of nonhomogeneous densities and elastic parameters that affect earth tides are among the variables that should be investigated and accounted

for in geodetic leveling. They may not account for the large discrepancy between the geodetic and oceanographic leveling results, but they will eliminate any traces of suspicion on the reliability of the geodetic leveling.

On the basis of the precise geodetic leveling results, the discrepancies with oceanographic "leveling" could be reconciled by re-examining the fundamental assumptions of oceanographic "leveling" (which is a theoretical computation and not direct physical measurement) and its associated physically undefinable reference level.

3.4 Establishment of Ground Truth

The yardstick for independent calibration, evaluation, and validation of performance of hardware and software models in operational field conditions has come to be known as ground truth. For instance, if a new satellite-borne system is being flown to measure ocean wave heights and direction, ground truth is required to calibrate and check out its performance. In this case, the ground truth consists of measurement of ocean wave heights and direction nearly simultaneously with the satellite measurements in some chosen test site by a proven and independent technique or system. In short, the establishment of ground truth is essentially the choice of (1) proven independent technique and/or system, and (2) a test site for checking out another technique and/or system, and (3) the independent measurement of the relevant parameters at the test site at the required time(s).

3.4.1 User Needs and Requirements

The previous sections have outlined various problems in marine geodesy and ocean physics and unavoidably associated satellite technology. It has been shown how mankind stands not only to benefit from the solution of these problems, but also must in fact resolve most of these problems in this decade to preserve man and his environment, and prevent international conflicts over boundaries and marine territorial claims. The timely and economic solution of these problems demand the establishment of new hardware and software models whose performances must be calibrated, evaluated,

and validated. Consequently, there is a need for the establishment of ground truth for marine geodesy and ocean physics.

A need exists for establishing a geodetic standard at sea against which accuracy criteria and capabilities of various positioning and surveying systems can be determined. Also, there is a need for establishing several geoidal profiles in support of satellite altimetry for both instrument calibrations and evaluation of data and processed results. Most ocean physics problems have been shown to require satellite technology for their timely and economical solutions on a global scale as a criterion for meaningful environmental monitoring and prediction. The establishment of the required ground truths for these ocean physics problems presents a challenge to engineers and management (61,83,86,88,90,108,109,119,123,136).

The first general requirement of an effective ground truth is that its quality must be as good or better than that of the model to be checked out. Proven conventional hardware does not exist for most ocean geodesy and physics needs. Thus, for instance, bistatic radar for sea-state monitoring is being developed (128). The second general requirement of an effective ground truth is that the characteristics of its parameters be exactly identical to those of the parameters that the new hardware and software models are designed to measure. For instance, independently determined geoidal profiles that constitute some of the ground truths for satellite altimetry should be identical to those expected from satellite altimetry in scale, shape and orientation.

The geoidal aspect of satellite altimetry ground-truth requirements has two phases. One is purely instrumental calibration of the hardware to ensure that the resultant altimeter height measurements have known and correct scale. The second is geodetic validation of the geoid deducible from satellite altimetry. This latter requirement is extensively discussed in the Proceedings of the NASA/NOAA/NAVY 1971 Conference on Sea Surface Topography from Space (21,61).

3.4.2 Problems in Satellite Altimetry Instrumental Calibration

The problems in satellite altimetry instrumental calibration are related to geoidal requirements and the implications of defining an accurate

satellite orbit. Use of nearly simultaneous range measurements, from four or five tracking stations to the satellite, is considered as an efficient approach for this purpose and has received considerable attention (22). A detailed review of the results of the referenced report indicates that the technique should receive more attention for unique determination of the satellite orbit. The application of this technique to satellite altimetry calibration involves several problems which are discussed below.

The fundamental equations in the report require the computation, at each tracking station, of earth-centered X, Y, Z coordinates and station radius vector, r, from the center of the earth. The relevant equations can be rewritten as

$$X_i = (M_i + h_i) \cos \varphi_i \cos \lambda_i \tag{3.5}$$

$$Y_i = (M_i + h_i) \cos \varphi_i \sin \lambda_i \tag{3.6}$$

$$Z_i = \left[M_i (1 - e^2) + h_i \right] \sin \varphi_i, \tag{3.7}$$

where

$$r_i = (X_i^2 + Y_i^2 + Z_i^2)^{1/2} \tag{3.8}$$

$$M_i = a_e (1 - e^2 \sin^2 \varphi)^{-1/2}$$

a_e = equatorial radius of reference ellipsoid used to approximate the earth's figure

e = eccentricity of the reference ellipsoid

φ_i and λ_i = geodetic latitude and longitude, respectively, of Tracking Stations (i) referred to the reference ellipsoid

$h_i = H_i + N_i$ = height of station (i) which, by implication of Equations (3.5, 3.6, and 3.7) must refer to the ellipsoid and not the geoid

H_i = height of Tracking Station i above geoid (or mean sea level)

N_i = absolute geoidal undulation at Station i.

The satellite's earth-centered X, Y, Z coordinates have to be used to compute R, which is the radius vector to the satellite from the earth's center. Similarly, the radius vector, R_o, from the earth's center to the corresponding subsatellite point on the ellipsoid can be computed. If at the subsatellite point (e.g., in a test area) the absolute distance K_s of the mean instantaneous sea surface (MISS) above the ellipsoid is known then the height (D) of the satellite above the MISS (see Figure 3.2) is given by

$$D = R - (R_o + K_s) \quad , \quad (3.9)$$

where

$$K_s = N_s + H_s \quad (3.10)$$

H_s = height of mean instantaneous sea surface above geoid (mean sea level)

N_s = height of geoid above reference ellispoid and, by the implications of Equations (3.5) to (3.10), it is the absolute geoidal undulation.

The determided D, corrected for the small difference between the mean instantaneous sea surface topography and the radar-defined electromagnetic mean surface, is the parameter to be compared with the direct altimeter measured range as a means of calibration in the field.

Calibration requirements at test sites are indicated by the following discussions. From the above developments, considering Tracking Sation i (in the close proximity of the subsatellite point) in the approximate determination of R and using Equation (3.9),

$$R = f_1 (H_i, N_i)$$

$$K_s = f_2 (H_s, N_s)$$

$$D = f_3 (H_i - H_s + N_i - N_s) \quad . \quad (3.11)$$

Errors in N_i and N_s that are of the same magnitude and direction will tend to cancel each other when D is computed from Equation (3.9), as shown by Equation (3.11). For this reason, it is expected that highly accurate measurements of relative differences in geoidal undulation in the test area will suffice for the purpose of calibrating the satellite altimeter instrument. However, even these differences must be differences in absolute geoidal
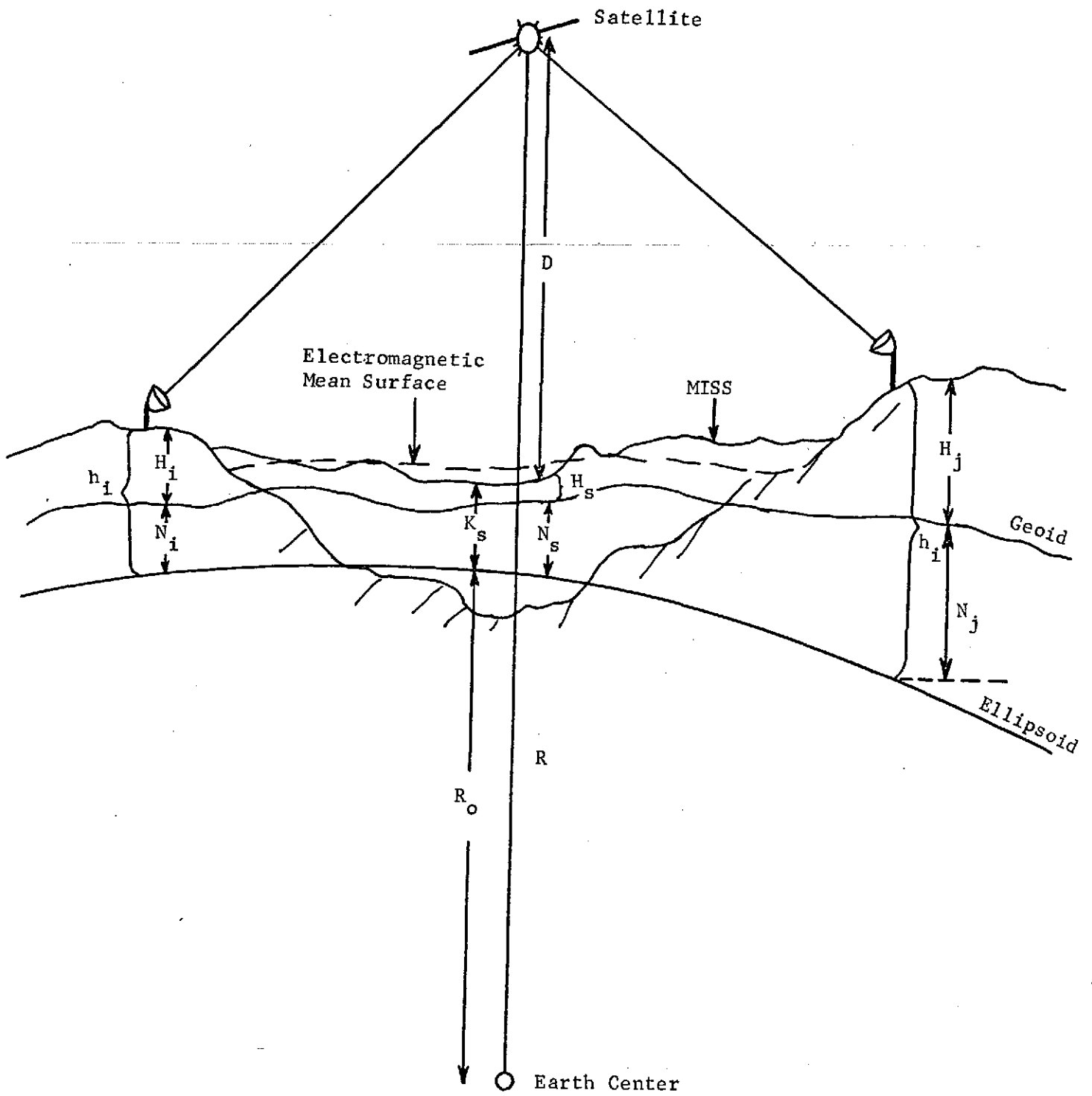
FIGURE 3.2   INSTRUMENTAL CALIBRATION OF SATELLITE ALTIMETRY

undulations in the area. The various techniques by which such differences in absolute geoidal undulation can be determined are given in reference (61).

The physical meaning of absolute geoidal difference is that the scale of N_i, N_j, and N_s (Figure 3.2) is the same but is not known exactly, and the measurements are relative to the center of mass of the earth. In other words, a surface centered at the earth's center of mass and parallel to the true geoid in the test area is shown. Most conventional geoids, do not satisfy the requirements of being earth centered and parallel to the true geoid owing to the type of measurements and data reduction techniques which have been employed in determining them, as shown in Table 3.2 (61).

The above considerations are adequate only for instrumental calibration of the altimeter. The role of sea-state determination in this process depends on the calibration accuracy desired. Such calibration cannot be more precise than the errors in the geoidal undulation differences and sea-state determination.

Absolute geoidal height differences implied in the above formulations are not the same as geoidal height differences from a "relative" geoid in the geodetic sense.

The ultimate geodetic goal is to determine an absolute geoid with the correct shape, scale and orientation. To achieve, this, geoidal heights in the test areas should be absolute and of correct scale. The geoid that geodesists must define for oceanographic, geodetic, space, and orbit computations must be absolutely oriented and correctly scaled.

Consequently, the following general conclusions can be made:

(1) Differences in the heights for various points on the geoid, relative to others in a test area, can be used for field calibration of satellite altimetry hardware.

(2) Differences in the heights of the geoid used must be referenced to the earth's center and define a surface parallel to an absolute geoid and not a relative geoid.

(3) The accuracy of the geoidal height differences at the test site must be similar to the accuracy of the absolute geoidal heights assumed at the tracking stations. This ensures that systematic errors cancel out as much as is possible.

(4) Other ground-truth data such as sea state are required, depending on the calibration accuracy desired.

(5) Error analysis of the components involved in Equations
(3.5) to (3.10) should be conducted. Another independent
investigation into special-purpose orbit determination for
satellite altimetry should be conducted. These steps will
ensure that consistent guidelines are stipulated for ground-
truth-data collection and also that satellite altimetry will
result in determination of the true geoid required.

3.4.3 Problems in Design and Numerical Analyses in Geodetic Adjustments and Orbit Computations

Battelle's investigations into the applications of satellite
technology for high-precision measurements to solve earth and ocean environ-
mental problems reveal that instrument technology, or instrumental accuracy,
is more than an order of magnitude ahead of accuracies achievable through
current data reduction and analytical processing techniques (62). This gap
exists because the mathematical models employed in most data-processing
techniques for these purposes are only approximations of the physical
models of the experiments. Equally important but often neglected is
establishment of the statistical model that relates the physical model to
the instrumental capabilities and unavoidable random and systematic errors.
Furthermore, undue emphasis has been placed on computing results without
establishing stability of numerical equations and statistical confidence.
Also, reliable preanalysis of mathematical models with efficiently simulated
data to investigate the influences of geometric configuration, spatial dis-
tribution of data, and the required quantity and quality of data will lead
to effective designing of experiments and cost reductions.

Adequate analytical techniques that can be judiciously employed
to bridge this gap have existed for centuries but have not been fully
exploited now that electronic computers are available. Parameter weighting
applied to least-squares adjustments by the method of intrinsic parameters
is one obvious answer (59). In the application of satellite technology to the
solutions of the earth's environmental problems, there is need to emphasize
and/or improve on the use of the following in every element of process
design and numerical analysis.

(1) The physical and statistical models employed in data
processing.

(2) Modelling uncorrected systematic errors by efficient
use of parameter weighting and statistical analysis.

(3) Investigation of instability of equations, convergency and the obtainment of unique solutions. For this, matrix norms, condition numbers, random numerical perturbation, and correlation coefficients are tools for detecting instability. There are techniques such as numerical equalibrating, parameter weighting, and solution by conjugate gradient that can accommodate most instabilities in the solution of equations.

(4) Evaluation test statistics for: (a) the variance factor using F-ratio or X^2 tests to investigate the correctness of physical and statistical models, the existence of unmodelled systematic errors, and the influence of round-off errors; (b) station or satellite position accuracy using a variable confidence ellipsoid for assessing three-dimensional coordinates and extraction of confidence intervals and correlation coefficients from a correctly computed variance - covariance matrix; (c) evaluation of station positions not only by computing chord lengths but also using the associated direction cosines in any chosen coordinate system.

(5) Rigorous simultaneous solution of range and range rate data for computation of satellite orbits from more than three tracking stations.

The resolution of the problems outlined here should help bridge the gap between technology and data processing in

(a) Orbit computations and trajectory analyses
(b) Adjustment of varying precision terrestrial geodetic networks
(c) Interconnection of satellite and conventional networks and recovery of scalar and angular distortions
(d) Satellite altimetry orbit computations and data analysis
(e) High-precision terrestrial and marine geodetic adjustments.

4.0 SATELLITE AND CONVENTIONAL TECHNIQUES FOR RESOLVING MARINE-GEODESY AND OCEAN-PHYSICS PROBLEMS

The previous chapter discussed the major problems in marine geodesy and ocean physics and the benefits man stands to derive by resolving these problems. Existing conventional techniques, operational, and planned satellite technology for resolving these problems are examined below.

4.1 Marine Geodetic Position Determination - Ocean Surface

Some of the techniques developed for land use that can be applied at sea are: (1) satellite techniques, (2) surface-based techniques, and (3) aircraft techniques. In addition, the very long baseline interferometry (VLBI) technique has potential application for similar geodetic measurements and is extensively discussed.

4.1.1 Satellite Techniques

The two satellite techniques most recently experimented with are the Doppler and C-band radar ranging systems. The Doppler navigation satellite system has been in operation at sea for several years to provide ship-position information. There are many published reports and articles on the use of Soppler satellites for navigation (55,67,121,124,137,139). Most of this literature describes the various types of receiver equipment available, the integration of other navigation systems and computers with such receivers, and some results obtained. Most navigation applications of Doppler satellites are aimed, of course, on positioning the ship while under way. Ship positions are determined, in terms of latitudes and longitudes, from a single satellite pass by measurement of the Doppler shift of the transmitted satellite signal. Accuracies reported for a fix from a single pass vary between 100 m and 1000 m, depending on how well certain factors such as geometry of pass, ship speed and heading, elevation angles, and number of usable Doppler counts are accounted for.

Several studies and experiments relating to the various types of errors affecting the accuracy of satellite fixes have been reported (69,74,77,99,100,131,157). However, most of them are either theoretical or are based on experiments at fixed land sites. It appears that no published detailed work based on experimental data has been reported on the accuracy of the Doppler technique for determining the three-dimensional coordinates of ocean-surface positions.

A theoretical study showing the dependence of the Doppler navigation satellite position fix over a fixed site on the geometry of the satellite pass and the Doppler counts received was made for Shell Development Company (131). The conclusions were based on computed standard deviations. The effect of errors in the estimate of the antenna height and the ship's speed was studied and typical results were given. A postcomputation method which reportedly can reduce the error in the latitude by making use of the drift characteristics of the oscillators involved and hence solve for only the latitude and longitude was indicated.

An experiment with the Doppler satellite navigation was made at the Bedford Institute in Canada (157). Extensive tests were made over a period of 58 days, with over 700 fixes being obtained at the Institute and 70 fixes obtained aboard ship at the pier. The results indicated that the scatter of the fixes was not random. Systematic errors were found that were related to the pass of the satellite, i.e., whether east or west of observer or whether the satellite was traveling northward or southward. Systematic errors were minimized by selecting equal numbers of carefully selected passes from all available satellites, taking into account the orbital geometry considered above. A ±55 m rms scatter was obtained for 47 carefully selected passes.

From these experiments, the positions determined are not of geodetic accuracy (see Table 3.1). Besides, only two (latitude and longitude) of the three geodetic coordinates of each position were determined because it is impossible to solve for the three geodetic coordinates of a station with data from a single satellite pass. Without the use of coordinated ocean-bottom transponders to track a nonstationary ship, satellite multiple-pass data solution which can compute three-

dimensional coordinates cannot be undertaken. However, the use of SRN-9 Doppler data for a six-parameter (latitude, longitude, height, ship heading, ship speed, and Doppler frequency) was investigated (99). The three-parameter solution (latitude, longitude and frequency) and the six-parameter solution gave almost identical results for the derived geodetic latitude and longitude from the same set of observations. The paper, as presented, left some questions unanswered about effectively solving for six parameters from a single satellite pass observed from a nonstationary ship. The variances assumed as weighting criteria for the six-parameter solution were 10,000 times better than those for the three-parameter solution, although the same set of observations was used. No justification was given for this discrepancy in weighting criteria which could only tend to make the six-parameter solution appear more reliable than the three-parameter solution. The paper did not present values for the circular probable error from the three-parameter solution, as it did for the six-parameter solution. Consequently, the efficiency of one model over the other could not be assessed.

A technique based on multipass satellite data obtained from the Magnavox Short Doppler Receiver (integrated Doppler at 24-second intervals) was developed for determining the three-dimensional coordinates of fixed sites (138,139). Position-fix accuracy of 10 m was claimed. The technique is also applicable for fixing the position of offshore oil-drilling plat-forms. The technique is aimed at using as many of the available raw data as possible. It is based on a least-squares solution with weights assigned to each Doppler count according to its geometric effect on the three-dimensional coordinates.

The most limiting factors to the accuracy of Doppler satellite techniques are errors in orbital data (particularly in remote ocean areas where no tracking stations are available) and inaccurate knowledge of ship speed and heading as well as error in estimating the geoidal heights. If these errors can be eliminated, it is expected that accuracies comparable to those achieved on land can be achieved with the Doppler system. The most effective way to minimize or nearly eliminate such errors is to use ocean-bottom transponders and determine accurately the time varying positions of the ship relative to the transponders during satellite passes (69,83,109,114). About an equal number of north-south and

south-north passes of suitable geometry to the east and west of the observer should be used. The ocean-bottom transponders provide accurate values of ship speed and heading and permit direct solution for the ellipsoidal height. A postreduction using actual and not predicted orbital data should be performed. Therefore, the future should be bright for accurate Doppler application to marine geodesy, especially through the use of the Geoceiver, which is reportedly an improved Doppler satellite receiver compared with the SRN-9 receiver (38).

The use of C-band-radar ranging with the GEOS-II satellite to make geodetic measurements on land was demonstrated by the NASA/Wallops Station Group. For example, comparison of the results of the AN/FPQ-6 and the AN/FPS-16 C-band radars with the GSFC laser range measurements showed consistent agreement to within a few meters, indicating that C-band radar is capable of providing 2 to 5 m accuracy in ranging (163).

Marine geodetic positioning by the use of C-band radar ranging is attractive because it can provide independent measurement capability which is useful in calibration and evaluation of other systems. Furthermore, the accuracy of radar ranging techniques is not so severely degraded by inaccurate knowledge of ship velocity as in the Doppler techniques. Compared to the Doppler satellite equipment, the limitations of C-band radar use at sea are the cost, size, and availability of equipment on ships. However, there are several tracking ships in the U.S. alone which are equipped with C-band radars that can make significant contributions to marine geodesy.

Several shipboard tests have been conducted by NASA/Wallops and the Air Force Eastern Test Range for demonstrating the capability of C-band radar for establishing the coordinates of ocean-bottom transponders (73,96,97,113,134). Most of these tests were conducted on an "opportunity" basis. Therefore, preparation plans for ground tracking support were limited and this was reflected in certain incomplete results.

One investigator (73) gave practical and theoretical results of ship-location experiments by range measurements to the GEOS-II satellite. The results of controlled tests (near shore and using theodolite fixes of ship positons as control) showed standard deviation of about ± 16 to ± 35m

in latitude and longitude, respectively, from a single-revolution-orbit fit, and about ± 18 to ± 27m in two-revolution orbit fit. He also showed the results in a test with mid-ocean-bottom transponders. The standard deviation of a single fix from the C-band radar observation was about ± 47m and ± 76 meters in latitude and longitude, respectively. The difference between C-band-radar mean-position solution and transponder-indicated position of the ship by a different system was about ± 55 m and ± 40 m in latitude and longitude, respectively. The better results of the near-shore experiment were due to the accurate theodolite fixes of relative ship positions input as constraints in the solutions.

Once ocean-bottom transponder positions can be determined to an accuracy of a few meters relative to ship positions, the only remaining significant errors that will occur in using satellites for establishing marine geodetic controls are errors in orbital data, particularly in remote ocean areas where no tracking stations are available. In the future, satellite altimetry, drag-free satellites, and satellite-to-satellite tracking are expected to improve orbit determinations (11,152). Improved accuracies in three-dimensional positions are also expected in some future satellite systems (52,53,87). Studies are under way on the use of the present laser ranging system with the stabilized shipboard C-band-radar system. An accuracy of better than ± 10 m in determining the coordinates of marine geodetic points can be expected with a combined radar and laser system.

There are other satellite systems which are applicable to marine geodesy but have not been in common use, owing either to technical problems or equipment size and cost. The application of the SECOR satellite system to marine geodesy was discussed in Reference (126), but there is no indication that the author's proposal has been implemented. Another author (82) described a system for determining the geodetic position of a ship at sea based on the principle of photogrammetric satellite triangulation. This author used a gyrostabilized camera aboard a ship and several land-based cameras to simultaneously observe light from a satellite against a star background. Test results with the prototype reportedly claim that the expected accuracy is about 10 to 20 m (circular probable error).

Theoretical investigations were made on the applications of ranging to geostationary satellites for marine geodesy and navigation (84). Position fix by ranging to only three geostationary satellites was found to be grossly inadequate. A combination of a geostationary satellite and four other orbiting satellites in a different-but-synchronous orbit was recommended. The role of accurate timing and adequate global distribution of monitoring stations was emphasized. The use of an aircraft (whose position is determined from a five-satellite configuration) to photogrammetically locate five surface buoys, which in turn locate ocean-bottom transponders by acoustic ranging, was recommended. The estimated positional error of the transponders was 50 to 65 m. The method suggested had several weaknesses. These weaknesses included the requirement for both the transmitter and receiver to be on board each survey vehicle, assigned observer times that restrict availability of satellites, the impracticality of tethering buoys in deep oceans and the distribution of surface buoys required, and the resultant weak geometry for transponder location. The error analyses in the paper excluded the actual use of photogrammetric and acoustic error sources and used a large number of simulated observations with unduly optimistic aircraft positional and velocity error estimates. In spite of these weaknesses, the paper generated useful and theoretically possible ideas which can easily be modified for practical utility if costs were not an important factor.

Doppler satellites were used on land for determining geodetic positions of station coordinates to a consistency of (a) ±2 m based on 5-day observations of one satellite and (b) ±10 m based on two satellite passes observed within a few hours(26,27,65). Theoretically, a similar precision can be achieved at sea. However, because at sea the ship that must be used is nonstationary, its time-varying positions must be tracked by an array of ocean-bottom transponders and used to simulate a single position to be solved for from multiple-pass data of one or more satellites.

4.1.2 Surface-Based Systems and Techniques

The most useful surface-based techniques involve the use of electronic positioning systems and shipboard inertial systems. Several types of electronic positioning systems (i.e., LORAN, DECCA, OMEGA, LORAC,

RAYDIST, HI-FIX, AUTOTAPE, etc.) have been used to position oceanographic
and survey data which are ultimately displayed on maps and charts in terms
of geographic coordinates. The positions assigned to these data (usually
the result of intersection of electronic lines of positions) are either
converted to or arbitrarily assigned as geographic coordinates. Electronic
positioning systems are subject to range, environmental, and/or geometrical
limitations which act singly or in varying combinations to degrade the
quality of positioning data. The rated capability of short-range high-
frequency systems of 5 to 100 m positional precision can meet the pre-
cision requirements for some marine geodetic operations up to distances
of 200 to 300 km from shore (7,55,89,109,148). Beyond these distances,
the lower frequency systems such as LORAN and OMEGA are used and they
do not meet the positional accuracy requirements in marine geodesy.

The various problems associated with the positioning systems
and their implication on survey results have been described by many
investigators (56,108,109,123,146). An electronic system may have
good repeatability of derived position. However, the real accuracy of
the systems or the resultant positions even at short distances from
shore (100 to 200 km) is not known (108,109,123). A need exists for
actual evaluation of the accuracy of all positioning systems, particularly
if they are to be used in highly accurate geodetic work. A relatively
inexpensive operational means for such evaluations which is within the
state of the art would be the establishment of several marine geodetic
ranges at various locations convenient for control of ocean explorations
(43,83,90,108,119).

Shipboard inertial systems have also been in use in various
marine operations. Starting from an initially known position, successive
positions are determined by the inertial navigator. They accumulate
errors with time, owing to gyro drift even in the absence of vehicle
motion, and therefore depend on periodic position updating by other
systems such as the electronic, astronomic, and satellite positioning
systems. Inertial positions and the corresponding geodetic positions are
not equivalent. Therefore, the practice of updating inertial positioning
systems with geodetic coordinates from systems such as satellites is
strictly inadmissible for geodetic work requiring high accuracy. It is,

however, a practical expedient in navigation. Furthermore, inertial navigation positions require an accurate definition of the gravity field (or the geoid) as an input to obtain geodetic positions. Also, gravitational and inertial effects cannot wholly be separated without outside noninertial information. The kinematic problems posed by these interactions are treated by Moritz (106,107). Thus, at sea, inertial positioning is so highly correlated with the geoid, or the deflection of the vertical which is not yet known accurately, that as of now, inertial coordinates are no substitutes for accurate geodetic coordinates, and the resolution of the problem is yet to be practically accomplished. In recognition of these interactions, several attempts have been made to use ship inertial navigation systems for measuring deflection of the vertical and determining the geoid at sea. These attempts are discussed later.

In spite of the above difficulties, inertial systems are being looked upon favorably and will probably play an increasing role in future positioning and in various surveying programs. They are being integrated with other positioning systems. If, among other things, the drift associated with inertial systems can be better controlled and if these systems are integrated with an astronomic positioning system capable of 1 arc-second accuracy in position observation at sea, they could become primary geodetic tools. A need still exists for their evaluation for marine geodetic applications.

4.1.3 Airborne Techniques

Airborne techniques employing distance-measuring equipment (DME) have been used on land for making independent distance measurements and for establishment of trilateration networks. The most commonly used technique in geodetic survey is line crossing. The line-crossing technique could be used to extend marine geodetic control at sea up to 800 km distance from shore or other known stations using only one surface ship, one aircraft, and a minimum of two land control points. The difference in the use of this technique at sea from that on land is that since one of the transmitters must be installed on ship, the motion of the ship must be determined accurately

during the time of line crossing. Examples of systems used on land in the U.S. are LORAC, SHORAN, HIRAN, and SHIRAN.

The feasibility of using a LORAC system with the line-crossing technique in establishing a marine geodetic control point at about 200 km from shore was demonstrated in an experiment conducted in the Pacific Ocean in 1968 (48,111). Independent distances were measured from each of three land control stations to the ship while it was positioned over three ocean-bottom transponders. A standard point error $\left(\sigma_p = \sqrt{\sigma_x^2 + \sigma_y^2} \right)$ of about ± 17 m was achieved in determining the horizontal coordinates. The results of the experiment further showed that the difference between the geodetic coordinates derived from the trilateration adjustment, which is more reliable because it had redundant measurements, and those derived from shipboard navigation systems was about 500 m. This can clearly indicate the need for establishing geodetic control points at sea, particularly in areas requiring accurate surveying and for checking and calibration of various positioning systems used in marine surveys.

4.1.4 Very Long Baseline Interferometry (VLBI)

In view of the emphasis under this task on the applications of satellite technology to high-precision measurements in earth and ocean physics, the utilization of new advanced technique such as VLBI, using either natural and/or satellite sources, was investigated. Most of the literature on VLBI is associated with radio astronomy. Few of the articles and reports reviewed dealt specifically with geodetic and earth physics applications, and these applications were discussed only in generalities. About thirty publications on this topic were reviewed and are listed in the references[*], none of the available literature examined problems definitely dealing with marine applications. A summary of the findings and current thinking on VLBI is presented below. A successful application of VLBI for determination of geodetic control on land and at sea as a reference system in land and sea boundary delineation will easily gain international acceptance because even now eastern and western nations are conducting joint VLBI experiments. The importance to world peace of

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[*] (23,24,30,34,37,39,44,45,64,91,94,98,105,127,129,130,132,153,154,158).

accepted boundaries and accepted physical-boundary-definition techniques at sea and on land cannot be overemphasized.

4.1.4.1 Background and Practical Applications of VLBI. VLBI has been successfully used in resolving up-to-now unresolved angular diameters of astronomical radio sources with great precision. It has great potential for high-precision measurement of long and intercontinental baselines and their spatial orientation. The successful application of VLBI for geodetic measurements would permit

(1) High-accuracy satellite tracking (absolute accuracies of a few centimeters) to meet many geodetic and oceanographic needs. These needs include satellite altimetry for ocean-surface mapping and determination of open-ocean tides and mean sea level.

(2) Determination of highly accurate absolute geodetic position at sea and on land.

(3) Establishment of intercontinental and interocean high-accuracy independent geodetic networks to improve international geodetic datum ties and resolve the disagreement in geodetic parameters from satellite geodesy. These results, of less than 20-m accuracy, vary from one investigator to another, even though most investigators claim precisions better than ±10 m. Such networks will furnish an independent check for the geodetic satellite results.

(4) Measurements of polar motion.

(5) Establishment of an absolute reference coordinate system for space, earth, and ocean physics research.

(6) Direct measurements of the magnitude and direction of sea-floor spreading.

(7) Investigation of continental drifts and the correlation with sea-floor spreading to permit quantitative and qualitative identification of the real physical mechanisms of these hypothesized motions.

Very long baseline interferometry (VLBI) techniques have recently been developed for radio astronomy measurements. The technical advance which has allowed the use of a baseline of thousands of kilometers in extent has been the development of highly coherent and stable reference frequency and timing devices such as the rubidium and cesium atomic standards and the hydrogen masers.

To date, these long-baseline techniques have been applied primarily to the measurement of the angular diameters of stellar radio sources of .001 second of arc or less. Considerable interest has been exhibited, however, in the use of VLBI techniques for the precise measurement of distance. In principle, the error in a measurement of baseline length using VLBI techniques would be independent of the magnitude of the baseline length--a very desirable feature for very long baselines.

So far, it appears that JPL has achieved limited demonstration of geodetic baseline-measurement capability employing VLBI technique(153,158). The lag in applying VLBI techniques to distance measurements for geodetic purposes is, to date, primarily due to the fact that, although it is relatively easy to operate a VLBI system to produce an interferometer with a very fine fringe spacing, it is difficult to identify a particular fringe or group of fringes. As a result of this difficulty of distinguishing a particular fringe from the several million or billion fringes that exist, the fringe rate or the fringe-pattern change with frequency must be used.

In general, what is desired is a measurement of the differential phase path delay, $\Delta\varphi$, between the source and the two interferometer sites.

$$\Delta\varphi = \frac{-WD}{C} \{\sin \delta_B \sin \delta_S + \cos \delta_B \cos \delta_S \cos (L_S - L_B)\} \quad (4.1)$$

and the fringe rate is given by

$$F = \frac{WD}{C} \cos \delta_B \cos \delta_S \sin (L_S - L_B) (\frac{dL_S}{dt}) \quad , \quad (4.2)$$

where W is the radian frequency, D is the baseline distance, C is the velocity of light, δ_B is the declination of the baseline, δ_S is the declination of the source, L_B is the hour angle of the baseline, and L_S is the hour angle of the celestial source. Thus, in general, for a single

baseline and a single observation, the baseline distance and its orientation cannot be separated. Alternatively, Equation (4.1) can be expressed in terms of the space rectangular Cartesian coordinates X, Y, Z, of any two stations, i and j, that form the baseline:

$$C\tau = \left(\Delta X_{ij} \cos \delta \cos \theta + \Delta Y_{ij} \cos \delta \sin \theta + \Delta Z_{ij} \sin \delta \right) \left(1 + \eta \right), \quad (4.3)$$

where

$$\eta = \frac{\omega}{C} \cos \delta \left(X_i \sin \theta - Y_i \cos \theta \right)$$

$$\Delta X_{ij} = X_i - X_j$$

$$\Delta Y_{ij} = Y_i - Y_j$$

$$\Delta Z_{ij} = Z_i - Z_j$$

    C = velocity of light

    τ = the measured difference in arrival times of wave front at Stations i and j

δ, θ = declination and hour angle respectively of the celestial source

    ω = angular velocity of earth.

This is the form expressing the VLBI measurements as a function of the parameters of interest in geodesy, earth and ocean physics and space research. The successful application of VLBI to these disciplines raises a number of questions that can be answered by solution of the problems listed below. A review of the pertinent papers as listed in the references show that these problems are still awaiting solution. The precision with which the phase delay can be measured, exclusive of all other error sources, depends upon the bandwidth of the interferometer system for an incoherent source. The achievement of large effective system bandwidths presents a difficult hardware and data-processing problem, and a variety of solutions of uncertain validity have been proposed.

      In addition, errors will be introduced in the path-delay measurements by reference source errors, errors in time synchronization and atmospheric effects.

Considerable effort has been devoted to the achievement of highly accurate reference sources and satisfactory time synchronization between the two interferometer sites. In addition, a number of organizations are examining methods of compensating for the existing atmospheric errors. The atmospheric errors are due to both ionospheric and tropospheric effects, with the ionospheric effects dominating at lower frequencies and tropospheric effects at the higher frequencies. Since microwave frequencies are more desirable from both signal-to-noise ratio, and hardware standpoint, tropospheric effects are currently receiving the major emphasis.

In order to assess the capability of using VLBI techniques for geodetic, earth, and ocean physics measurements, it is necessary to examine in detail the interactions and trade-offs. On one hand are the achievement of a high-precision measurement of an individual baseline distance at the expense of complexity and cost in the associated hardware and data-processing procedures. On the other hand is the use of data of lesser precision for an individual baseline combined with geodetic adjustment techniques using multiple baselines, sources, etc., in order to achieve overall high precision. This requires a detailed examination of techniques for achieving high effective system bandwidths and resultant delay-measurement accuracy versus the associated hardware and signal-processing requirements, along with a detailed examination of the geodetic adjustment procedures that can be applied to VLBI data.

In general, there are five major areas that need intensive and efficient research. These can be broadly classified under

(1) Hardware

(2) Atmospheric - ionospheric and tropospheric

(3) Motion of receiver

(4) Type of celestial sources (artificial or natural) and determination of their precise locations

(5) Software problems in data reduction and analyses to accommodate problems in the above four topics.

A need exists to investigate the software problems and hence resolve the analytical problems associated with the use of VLBI to meet geodesy and ocean-physics objectives.

Specifically, the following geodetic analytical problems need to be investigated in some detail:

(1) Network configurations and avoidance of critical geometry for optimum use of VLBI, including configurations for operations in a geometric and/or dynamic mode, and considering, for each mode, the use of natural and/or satellite sources. Other related problems include the optimum number of network stations and the use of simultaneous or nonsimultaneous observations.

(2) Source coordinates.

(3) Modeling of atmospheric influences.

(4) Confirmation of and establishment of a correction model for the bending of electromagnetic propagations passing by the sun, associated with the theory of relativity.

(5) Determination of relative and absolute geodetic coordinates and orientation from VLBI data which requires establishment of mathematical models to adapt the data and computational techniques to methods of classical, spatial, or intrinsic geodesy.

(6) Adequate statistical modeling studies for optimum data reduction and analyses. Inadequacy of statistical models is currently the weakest component of data reductions and analyses in geodetic and orbit computations. At present, most hardware accuracies are several orders of magnitude superior to software accuracies.

These types of analytical considerations and their implications are discussed in Reference (62).

4.2 Marine Geodetic Control Determination - Ocean Bottom

The determination of the three-dimensional coordinates of geodetic control points at sea involves the solution of two problems: (1) determination of the survey ship's geodetic position in the chosen geodetic datum, and

(2) accurate location of the ocean-bottom-mounted markers with respect to the ocean-surface ship positions. Techniques for solving the first problem are discussed in Section 4.1. Many techniques for resolution of the second problem have been tried (42,60,68,115,116) with varying degrees of success. It is far from a completely resolved problem. The following is a review of operational techniques and systems used to relate ocean-bottom transponders to ocean-surface positions.

Acoustic systems are used almost exclusively to make measurements relating ocean-surface positions to the bottom. Most of the systems that have been used in recent experiments designed specifically for marine geodetic research consist of (1) three or four ocean-bottom transponders with power supplied by lead-acid batteries or underwater radio isotope power sources (URIPS) and (2) a shipboard system for interrogating the transponders, receiving their replies, and displaying travel time to them (111,115). In addition, velocity of sound is usually measured whenever possible at the time of experiment in the area of operation, or previously measured mean value for the area is used.

Another type of acoustic system has been developed and used in ocean search-and-recovery operations and in dynamic ship positioning associated with deep-ocean drilling operations (8,12,15). The system utilizes one transponder on the ocean bottom and three or four hydrophones (receivers) installed on the ship's hull (forward, aft, starboard, and port), forming short baselines.

The most commonly used technique for locating bottom transponders from ocean-surface measurements is acoustic line crossing. However, this technique has serious accuracy limitations and requires stringent control on ship's heading and speed and also requires accurately determined transponder depth (50,60,115). To overcome these limitations, three new techniques were developed at Battelle-Columbus for reduction of shipboard acoustic measurements made from different ship positions to ocean-bottom acoustic transponders (60,115,116). Each of these techniques has some advantages in certain applications. They are all capable of much higher precision than the line-crossing technique and are also briefly described below.

4.2.1 Acoustic-Line-Crossing Technique

The acoustic-line-crossing technique is similar in principle to the airborne-line-crossing technique used in geodetic trilateration networks on land where unknown positions can be computed from measured distances. However, in the acoustic line crossing, the transponder depths are first measured with the shipboard system (while the ship maneuvers directly over the transponders) and these depths are then taken as fixed parameters in the reduction of the acoustic slant ranges to their horizontal components. The ship is allowed to travel at a constant heading, crossing the lines joining each two transponders, as shown in Figure 4.1.
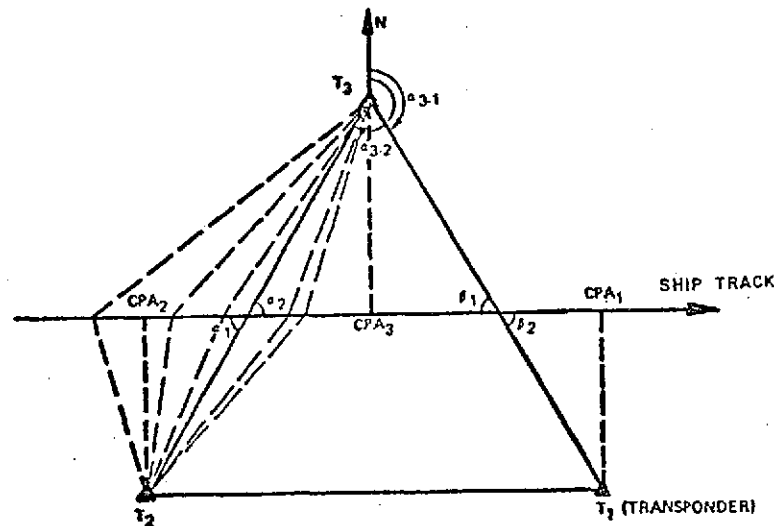
FIGURE 4.1 ACOUSTIC LINE CROSSING

The two-way travel time or the computed acoustic slant ranges to each transponder are continuously recorded. The horizontal coordinates of the transponders and their orientation are computed from the deduced minimum slant ranges, ship heading and speed, and the fixed depths. The solution can be obtained by a least-squares curve fitting (to determine minimum sum of horizontal ranges), or graphically by plotting the horizontal ranges

against time and obtaining the vertex of the parabola. In spite of its
deficiencies, this technique appears to be the most commonly used because
it is simple in design and easily understood by even nongeodesists who
engage in ocean-bottom position location at sea. A detailed discussion
of the technique and how it was applied to data from the Atlantic Ocean
is presented by Hart (68). Its use and results in two other experiments
are also discussed (111,113-115).

4.2.2 Transponder-Array Location by Coplanar Ranges

Transponder-array location by coplanar ranges is a modified
line-crossing technique that eliminates most of the assumptions causing
errors in the conventional line-crossing technique. With this technique,
developed at Battelle, the depth of each transponder and the geometry of
the transponder array can be analytically determined. The technique
involves a three-dimensional, weighted-least-squares solution, utilizing
near-coplanar slant ranges in the various vicinities where the ship crosses
the vertical plane containing any two transponders. The technique is
amenable to statistical analysis of the observations and the adjusted
parameters. It can also furnish geodetic orientation of the array if the
geodetic coordinates (from satellites or other electronic positioning
system) of at least two adequately separated ship positions and the
corresponding slant ranges to at least two transponders are determined.

4.2.3 Transponder Location From Surface Positions (TLSP)

TLSP involves a weighted-least-squares solution for determining
simultaneously the three-dimensional coordinates of ocean-bottom acoustic
transponders using acoustic slant ranges and surface ship coordinates. It
is based on the principle of intersection of a minimum of three slant ranges
from three known and noncolinear points to an unknown point (see Figure
4.2 (113,115). The technique includes application of statistical analysis
for determining adequate weighting criteria before the adjustment. The
adjustment is performed in a three-dimensional Cartesian coordinate system

(X,Y,Z) whose primary plane is in the equator and whose primary axis is parallel to the mean rotational axis of the earth.

The TLSP computer program incorporates a ray-tracing subroutine that corrects for acoustic refraction as it computes the acoustic slant ranges from the curved path travel times using velocity-of-sound profile data for the area. The advantage of this technique is that it determines the depth by a least-squares adjustment of several ranges in contrast to, for example, line crossing, where the depth to the transponder is measured and then held fixed throughout the computation.
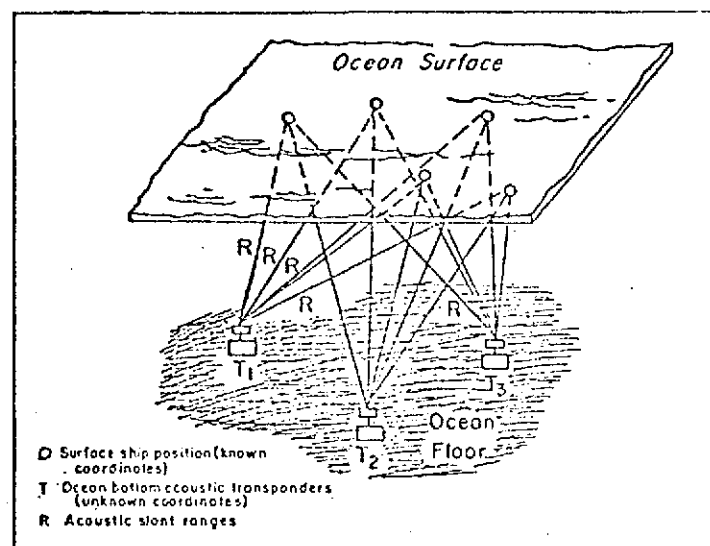
FIGURE 4.2   PRINCIPLE OF INTERSECTION IN TLSP TECHNIQUE

4.2.4   Horizon-Coordinates Technique

The application of the horizon-coordinates technique to adjustment of marine geodetic measurements was developed in order to avoid the use of estimated geoidal heights as done in TLSP. It solves directly for depth of the transponders and permits more flexibility for introducing constraints in a generalized least-squares solution with parameter weighting (60).

TLSP in horizon coordinates merely performs the adjustment in a local horizon-coordinates system, a, b, and c, centered at the transponder. The a-axis is positive northward, the b-axis is positive eastward, and the a-b plane is parallel to the horizon and situated at the intersection of the local vertical of the transponder and the ocean surface. The c-axis coincides with the local vertical so that the determined c-coordinate is the depth of the transponder below the transducer. The geoidal undulation need not be known or assumed. In the earth-centered Cartesian coordinate system, let

$$
\begin{bmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{bmatrix} = \begin{bmatrix} X_s - X_t \\ Y_s - Y_t \\ Z_s - Z_t \end{bmatrix} , \tag{4.4}
$$

where the subscripts s and t refer to the ship transducer and transponder, respectively; then the relationship between a-b-c and X-Y-Z systems is given by (59)

$$
\begin{bmatrix} a \\ b \\ c \end{bmatrix} = \begin{bmatrix} -\sin \Phi \cos \Lambda & -\sin \Phi \sin \Lambda & \cos \Phi \\ -\sin \Lambda & \cos \Lambda & 0 \\ \cos \Phi \cos \Lambda & \cos \Phi \sin \Lambda & \sin \Phi \end{bmatrix} \begin{bmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{bmatrix} , \tag{4.5}
$$

where

Φ = astronomic latitude of the transponder, positive northward

Λ = astronomic longitude of the transponder, positive eastward.

The geodetic φ and λ are substituted for the unknown astronomic Φ and Λ.

The techniques described in Sections 4.2.2 through 4.2.4 are primarily three-parameter solutions. In addition, a five-parameter solution treating as free variables the three coordinates of the transponders, the acoustic system timing bias, and the sound velocity has been developed (60). The functional relationship between the five parameters is expressed as,

$$
A \cdot \Delta X + f(X^\circ) = (T^b + \Delta T)(C^b + \Delta C) + V \quad .
$$

where T^b is observed one-way time, C^b is assumed sound velocity, ΔC is true minus assumed sound velocity, ΔT is the correction to observed T^b, X° is a set of approximate coordinates and V is residual of observations. The ill-conditioned normal equation resulting from the direct solution was remedied by introducing certain constraints regarding depth and velocity of sound through weighting the parameters.

4.3 Tracking of Ship Positions From Ocean-Bottom Transponders

Having determined the coordinates of the transponders by techniques described above, coordinates of unknown ship positions, can now be determined by several methods. The most common method involves use of the intersection of three acoustic slant ranges, corrected for sound refraction, from the ship to three transponders (95,114). This method or some variation of it has been used in navigation and is often referred to in the navigation literature as long baseline (1,49,54,92,124,149). The baselines are the distances between the ocean-bottom transponders which vary between 1 and 2 times the depth. Using this method, ship heights, for example, were recovered with a ± 1 m standard deviation (116).

Other methods in use involve direction and range measurements from a single bottom transponder to a fixed array of three or four hydrophones located on the ship. This is referred to as the short-baseline method, deriving its name from the short baselines (50 to 150 m) formed by the spacing of the ship hydrophones (less than 150 m). The directions are determined from measurements of the differences in the travel times of an acoustic signal to the hydrophones. This method is commonly used with drilling ships for dynamic positions (8,12,124,145) and is perhaps of lesser accuracy than the long-baseline method. However, the short-baseline method has not been evaluated for geodetic purposes.

4.4 Geoid Determination at Sea

Further improvement in the knowledge of the earth's gravity model and solution of certain problems in ocean dynamics would have to depend on either an adequate distribution of direct gravity measurements all over the earth or an accurate determination of a correctly scaled global absolute geoid. The latter alternative is one of the main objectives of satellite altimetry which should afford a more speedy and economical solution. However, this implies accurate determination of the absolute geoid in all oceans, which cover about 70 percent of the earth. There are several conventional and other new and untried techniques that can be

utilized. These techniques, their potential, and the problems involved in their utilization at sea are briefly described below.

The geoid is an irregular figure whose shape is not exactly like any known simple and geometric figure. The fundamental basis of all geoidal determination is to define the vertical linear departures (geoidal undulations) or surface tilts (deflections of the vertical) of the geoid relative to a rotational ellipsoid which is the best geometric approximation of the figure of the earth.

4.4.1 Astrogeodetic Technique

This technique employes the difference in the direction of the gravity vector and the ellipsoidal normal of a station, which is termed astrogeodetic deflection of the vertical, ϵ. The direction of the gravity vector is defined by the determination of astronomic latitude, Φ, and longitude, Λ, while the geodetic latitude, φ, and longitude, λ, define the direction of the ellipsoidal normal. The general relationships of these parameters are expressed by

$$\xi = \Phi - \varphi \tag{4.6}$$

$$\eta = (\Lambda - \lambda) \, \text{Cos} \, \varphi \tag{4.7}$$

$$\epsilon = \xi \, \text{Cos} \, \alpha + \eta \, \text{Sin} \, \alpha \tag{4.8}$$

$$N_B = N_A - \int_A^B \epsilon \, dS \quad , \tag{4.9}$$

where ξ and η are the meridian and prime vertical components of the deflection of the vertical, respectively, and N_A and N_B are the geoidal undulations at points A and B separated by a distance dS in an azimuth α.

On land, this technique has many disadvantages. It can be adapted for use at sea, but the ocean environment increases the problems inherent with this technique. For the technique to be useful at sea, astronomic position determination accurate to 1 arc-second or better is required. This is the biggest drawback at sea where currently the best accuracy achievable may be about 10 to 20 arc-seconds. In addition, the geodetic latitude and longitude are equally weakly determined at sea. They

are usually based on a local geodetic datum and hence result in a relative geoid instead of an absolute geoid. The scale and shape are usually "correct", but the absolute orientation is usually incorrect. The accuracy rapidly deteriorates and the magnitude of the geoidal undulation excessively increases away from the datum origin.

The practical implementation of the astrogeodetic technique at sea has been reported by several authors (36,40,150). von Arx computed both astrogeodetic and gravimetric deflections of the vertical and geoidal undulations for a 240-km north-south profile across the Puerto Rico Trench (150,151). The precision of his astronomic positioning instrument is stated to be ± 12 arc-seconds (rms). The accuracy of the geodetic positions was not given. Although, for the overall accuracy of the resultant astro-geodetic arc, von Arx's confidence in his results is summarized by his statement that "the accuracy obtained is barely comparable with that achieved by Eratosthenes two millenia ago when he estimated the cir-cumference of the earth", his effort is a significant, if not the first, contribution.

Another determination of the astrogeodetic deflections of the vertical across the Puerto Rico Trench was made (40). Basically, the authors computed the deflection of the vertical as the difference be-tween the geodetic coordinates as furnished by LORAC and the coordinates indicated by SINS (Ship's Inertial Navigation System). SINS output is strictly not a true astronomic quantity. The resultant deflections are, therefore, not truly astrogeodetic. The stated estimate of the precision of the geodetic coordinates was about ± 200 feet (or approximately ± 2 arc-seconds).

The two determinations of astrogeodetic deflections of the vertical in approximately the same vicinity by the above investigators differ at times by up to 70 arc-seconds. Their reports do not afford the details necessary to assess or account for the large discrepancies. This situation emphasizes the need for more and better-controlled marine geodetic research with improved hardware, measurement techniques, and geodetic and statistical analysis procedures.

Used alone, the astrogeodetic technique is least desirable for marine determination of an absolute geoid. Other potentially useful modified versions are discussed later.

4.4.2 Astrosatellite Technique

The principle of this technique is basically the same as that of the conventional astrogeodetic. The only difference is that the geodetic latitude, longitude, and ellipsoidal height should be determined from dynamic satellite geodesy solution (61,97,117,135).

This technique has two important merits. First, the resultant deflections of the vertical and hence the geoid are absolute. Second, the ellipsoidal height, h, that can be directly determined is easily translated to sea-level equivalent and gives the value of the geoidal height directly because

$$h = H + N \quad , \qquad (4.10)$$

where H, the orthometric height, is zero at sea level and N is the geoidal undulation.

The problems in this technique include inaccuracy in the determinations of (1) satellite-orbit dynamics due to earth-gravity-model errors, inadequate distribution of tracking stations, and other ill-known perturbation forces, (2) geodetic and astronomic coordinates, and (3) the actual mean sea level relative to the observing antenna. The motions of the ship inhibit making redundant determinations of coordinates for any given point. This latter problem can be alleviated by referencing the time-varying positions of the ship to ocean-bottom-mounted acoustic transponders as described earlier.

The first practical investigation of this technique was included in the "Ocean Surface Mapping Experiment" conducted across the Puerto Rico Trench in 1970 by NASA. The data analysis is still in progress. Results from direct computation of h and hence N to obtain a geoidal profile are described by Stanley, et al. (97).

4.4.3 Gravimetric Technique

The classical determination of the geoid is based on the integration of gravity anomalies all over the earth by the use of Stokes' formula. The result is an absolute geoid with "correct" orientation and shape but "improper" scale. On land, various techniques have been devised to resolve the scale problem whose geometrical meaning is a redefinition of the equatorial radius of the reference ellipsoid involved in the computations of the gravity anomaly(71).

Until recently, at sea the gravimetric technique has been exclusively used, employing either the Stokes' integral or the determination of absolute deflections of the vertical (using Vening Meinesz formulas) which are then integrated as in Equation (4.9). The weaknesses of the vertical-deflection method are the requirements for a dense gravity net around the computation point and the need for a known absolute geoidal undulation at one point of the integration if an absolute geoidal profile is to be obtained. Gravity measurements are currently being conducted at sea for the determination of the geoid (18,144). The latest results on computed geoids for the U.S. North Atlantic and Western Europe from a combination of gravity and satellite data are given in Reference (142).

The greatest limitation of this technique is the problem arising from the economics and politics involved in measuring gravity all over the earth. At sea, other problems include the inaccuracy of gravity and ship-velocity measurements, the lack of base stations for adequate control, and the paucity of available observations. Used alone, this technique will require several decades to achieve the determination of a global geoid because of the problems outlined. However, the use of satellite technology and geodetic acoustic techniques with ocean-bottom transponders can provide the needed base stations as well as accurate ship-velocity information. To obtain 1-mgal accuracy in gravity measurement at sea requires accurate knowledge of the ship's true velocity to about 0.1 knot. This source of error alone makes it currently impossible for marine gravity measurement to be more accurate than the ±5 mgal anticipated accuracy by many users.

4.4.4 Astrogravimetry Technique

Astrogravimetric leveling, which is basically dependent on a combination of astrogeodetic and gravimetric determinations of the deflections of the vertical (103), appears never to have been used at sea (61). It combines all the strengths of both the astrogeodetic and gravimetric determination of the geoid. It also inherits the inaccuracies due to field observations.

The technique permits more widely spaced astronomic/geodetic stations, between which a local dense gravity net is used to interpolate for deflections of the vertical. Consequently, in any locality, an absolute geoid with "correct" shape, scale, and orientation can easily be deduced. It is probably the best technique for determining in any locality the ground truth for calibration and evaluation of geoidal determinations from other techniques, such as the satellite altimetry technique discussed below.

4.4.5 Satellite-Orbit Analysis

Geoid determination by this method is based on the analyses of perturbations of an artificial satellite orbit due to the earth's gravity field. At satellite heights, small-scale features of the geoid cannot be detected by this technique. While it does give a reliable general outline of the main features of an absolute geoid, this method alone will not provide a detailed and accurate geoid. However, in combination with terrestrial and marine gravity measurements, the technique does have high potential, but retain all the problems of gravity work (164-166).

4.4.6 Satellite Altimetry

Details of this method for determination of the geoid have been presented by several authors (63,66,76,93,133,136,155,156). The principle is to measure, by radar altimetry, the vertical separations

between a well-defined satellite orbit and the ocean surface as a means
of computing the geoid at sea. The probability for the success of this
method is high. However, it does require accurate ground control or
ground truth at sea to establish its effectiveness. An accuracy of 1 to
3 m in determining the geoid is welcomed by geodesists. Accuracy of
better than 1 m is required for many precise oceanographic computations.
Two altimeter programs being planned in the U.S., the first on the Skylab
and the second on GEOS-C (136), are anxiously being awaited.

5.0 ROLE OF GEODESY IN DEVELOPMENT AND UTILIZATION OF THE OCEANS
AND POTENTIAL APPLICATION OF SATELLITE TECHNOLOGY

5.1 Introduction

Development and utilization of the ocean resources in socio-
economic, international, and diplomatic/political areas will increasingly
place stringent demands on specialized ocean activities which cannot be
adequately satisfied without marine geodesy. These demands are, in some
cases, related to positional accuracy requirements, increased number of
surveys being conducted with the trend toward large-scale maps and charts,
all demanding greater detail. As the distance from shore to the ocean
regions undergoing economic development becomes greater along with ocean
depths, accuracy requirements will become more important because of the
increased operating and exploration costs.

Because, at present, the marine environment is so little under-
stood, so hazardous, and so vast, any advances in marine geodesy and
oceanography can have far-reaching influences. Some concerns of these
two sciences--the dynamics of the oceans, gravity and magnetic fields,
ocean-floor spreading, the size and shape of the earth, and sea-surface
and ocean-bottom topography--are of obvious interest for many practical
programs. The relationship of other concerns--such as global tectonics,
geoid determination, and earth dynamics and kinematics--is less obvious
but nonetheless important to consider if practical goals are to be served
in the most efficient and economical manner. Without correct, broad
understanding of ocean phenomena, it is impossible to proceed in any
direction with a high level of confidence. Moreover, if early decisions--
especially those that affect international collaboration and cooperation--
are incorrectly made, considerable wasted time and effort, unnecessary
expense, and confusion and frustration can result.

For all practical purposes, satellite technology has the best
potential for establishing marine geodetic control points, particularly
in the deep ocean. Also, the ability to determine an accurate absolute
global geoid through satellite altimetry makes satellite applications to

marine geodesy and ocean physics of practical and scientific importance
in achieving effective use of the seas and their environment (11,85,86,94,109).

5.2 Practical Geodetic Applications

Four important practical geodetic-applications areas are
discussed:

(1) Bathymetric mapping and charting

(2) Territorial boundaries at sea

(3) Ground truth

(4) Gravity measurement.

The relevancy of marine geodesy to representative national and
international activities is summarized in Table 5-1. The following discus-
sion is limited to those activities listed that we believe will benefit
from the various marine geodesy areas shown. The relevancy of marine
geodesy to these activities is given semiquantitatively on a scale of
decreasing relevancy from 1 to 3. The use of such a scale, although not
exact, tends to give a general idea on the degree of relevancy. In cer-
tain areas the relevancy is indicated by the letter P. This indicates
that while relevancy has not been directly demonstrated recently developed
geodetic techniques, which resulted in high precision, may have potential
for application.

Satellite-technology involvement in margine geodesy and ocean-
ography is imperative in at least four major areas: (1) establishment of
geodetic control, (2) precise ship positioning, (3) mean-sea-level (geoid)
determination, and (4) ocean-physics applications. The technology needed
for these purposes has never been fully developed or exploited. The growing
national and international ocean-oriented interests and activities will
require greater emphasis on marine geodetic problems which are considered
to be heavily dependent upon satellite technology for their solution(1,2,9,11,13).
With the developing technology for precise geodetic measurements, particu-
larly for the establishment of marine control points on a worldwide basis,
satellite/marine geodesy should make direct contributions to marine sciences
and provide a basis for microstructural oceanographic surveys (17,19,51,66,
77,85,86,109,112,113,118,135,151,162).

66

TABLE 5-1. RELEVANCY OF MARINE GEODESY TO SELECTED
NATIONAL AND INTERNATIONAL OCEAN ACTIVITIES

	Marine Geodesy Areas[a]					
	Control Points	Ship Positioning	Ship Velocity	M.S.L. (Geoid)	Geodetic Adjustment	Surveying & Mapping
Practical Geodetic Applications						
Bathymetric mapping and charting	1	1	3	1	P	1
Sea boundaries	1	1	-	3	1	1
Ground truth	1	1	3	1	1	1
Gravity measurement	1	1	1	1	1	2
Environmental Prediction & Ocean Physics						
Air-sea interaction	P	3	-	1	-	3
Tides and mean sea level	1	1	-	-	P	3
Sea state	P	3	-	-	-	3
Tsunami detection	P	-	-	-	P	2
Ocean currents and transport	3	2	2	1	-	2
Waste disposal	2	1	-	-	-	1
Ice-sheets motion	P	1	-	-	P	2
Geology Geophysics & Resources						
Gravity surveys	2	1	1	2	3	2
Seismic surveys	2	2	-	-	3	2
Magnetic surveys	2	2	-	-	3	2
Geologic surveys	2	1	-	-	-	2
Pipelines and cable laying	3	1	1	-	-	1
Petroleum and gas	2	1	-	-	-	1
Solid minerals	1	2	-	-	-	2
International Relationships						
National security	1	1	1	1	1	1
Commerce	3	3	3	-	-	2
Search, rescue, and salvage	1	1	1	-	-	1
Scientific and Educational Applications						
Figure of the earth	1	1	1	1	1	1
Ocean spreading	P	1	-	3	P	1
Ship/satellite tracking and orbit determination	1	1	-	1	1	1
Inertial navigation	P	1	-	1	1	-

Examples of National & International Programs

Inter-Dec. of Ocean Expl.
Sea Grant
Global Atmos. Res.
Nat. Data Buoy Program
GEOS-C, Skylab, Appl. Tech. Sat.
Man in the Sea

All have varying degrees of applications and can benefit from marine geodetic and satellite techniques — they need special investigations.

(a) Number rating is as follows:
1 - Primary Relevance
2 - Secondary Relevance
3 - Tertiary Relevance
P - Potential Applications of Geodetic Techniques as explained in details in this section

5.2.1 Bathymetric Mapping and Charting

The importance of accurate surveying, mapping, and charting of the oceans can be appreciated to some extent if one considers the broad benefits that have been derived from these activities on land. The oceans make up approximately 70 percent of the earth's surface, and the marine environment--both surface and subsurface--presents many problems not encountered on land. The opening of the ocean frontiers will follow the history of frontier opening on land--accurate and detailed surveying, mapping, and charting are prerequisites for any real advancements (2,3,6,15,46,102).

The potential applications of marine geodesy and satellite technology to bathymetric mapping lie in three areas: (1) geodetic control, (2) accurate ship positioning and velocity determination, and (3) mean-sea-level determination. Bathymetric mapping is necessary for national economic development. There is an ever-increasing demand for accurate and detailed maps in the deep ocean in support of various important activities such as economic development of resources, monitoring and preservation of the environment, commerce, national defense, and a host of scientific activities. Economic and scientific enterprises require marine data at various map scales, between 1:2000 and 1:50,000(6,14,46). Military, search and recovery, Man-in-the-Sea, scientific, and transportation interests require data over a wider range of scales, from 1:2,000 to 1:1,000,000. Continuous position information is often required. Position errors tend to occur and often lead to unnecessary expense. According to an U. N. Report, the lack of a worldwide system of precise navigation hampers the conduct of surveys and imposes a limit on their value for charting purposes in mid-ocean areas (16). Furthermore, certain features on charts in the deep ocean can be subject to errors of many miles. Priority areas are those on the continental shelves, for navigation and exploitation of resources. Only about 10 percent of the ocean maps have acceptable accuracy (16). Since over 90 percent of the ocean areas have to be re-mapped, the lack of control presents excellent opportunities for employing both marine geodesy and satellite technology to conduct mapping systematically and with proper control to eliminate a future need for readjustment of the various datums as is now the case with land maps. The establishment of control will provide the increased accuracy required for detailed maps.

and eliminate the problems associated with incompatibility of land maps (based on national datums) with the newly constructed ocean maps (based on a worldwide satellite geocentric datum) (56). Since the charted depths are referenced to mean water lines, the determination of the geoid (mean sea level) is important for bathymetric mapping and charting.

5.2.2 Territorial Boundaries at Sea

The potential applications of satellite technology and marine geodesy to determination and identification of boundaries at sea lie primarily in (1) establishment of control points, (2) accurate ship positioning, and (3) detailed bottom surveying and mapping. Existing techniques for determining boundaries at sea are inadequate, whether for issuing oil, gas, and mineral leases or for establishing state, national, and international boundaries. Boundary lines at sea are hypothetical lines drawn on maps using map projection procedures and are not identifiable with physical markers as is the case on land. Lack of physical identification of these lines can cause disputes, and litigation often arises over political boundaries and lease claims* (41,51,81,90,109,110,112,122).

Marine geodetic control points could serve as the corner stones for identification. One possible way to establish boundaries is by establishing geodetic control at suitable sites. However, the problem of determining the boundary lines between the adjacent control points and identifying them from the surface by an operating vessel still exists. The use of an accurate satellite positioning system with suitable shipboard equipment to relate to the ocean bottom offers great potential.

5.2.3 Ground Truth and Standards

The lack of accurate ground truth at sea offers another potential application of both marine geodesy and satellite technology. Satellite

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*"....Now these boundaries between various jurisdictions must be accepted, must be recognized, must be definable, and they must be recoverable. And whether these boundaries are extended from shore or from shoreline features to various distances off shore, whether they are defined by underwater features themselves,such as isobaths or sea mounts,or whether they are defined by mathematical lines, such as meridians and parallels, they must be properly positioned, and this is where the job for the geodesist comes in. I don't believe he is always going to enjoy his role in this part of the field"(122).

technology not only has a definite role in the establishment of ground truth, but also benefits from it, as do other areas of ocean sciences and their applications. Ground-truth applications are related to (1) geodetic controls, (2) ship positioning, (3) geoid determination, and (4) ocean physics.

Position errors lead to undesirable or costly situations in matters related to international and territorial boundaries and waters, domestic and international lease boundaries, surveying, military operations, and search and recovery operations. The ability to evaluate these errors with greater confidence necessitates the development of standards and accuracy criteria to evaluate positioning systems and their geographic-coordinate-determination capability, upon which marine survey data are based(2,11,50,57,58,61,83,90,108,111,112).

Existing and future advanced satellite geodesy techniques offer the best potential for establishment of control points at sea, particularly in the deep oceans, where no other precise surface-based positioning systems exist. The geodetic control points are essential elements of ground truth as shown in Section 3. The need for ground truth was also discussed in that section. The problems of calibration and evaluation of all types of positioning systems, including satellite positioning systems will be alleviated with establishment of ground truth. If satellite altimetry is ever expected to meet its ultimate objective--a 10-cm accuracy in determining the mean sea level--it will require geodetic ground-truth information, both for accurate determination of absolute positions (three-dimensional coordinates) and establishment of suitable geoidal profiles in various areas of the oceans. The use of the Vanguard ship with its instrumentation systems, particularly C-band ranging to the GEOS-II satellite, has already demonstrated the potential for satellites in determining a geoidal profile (96,97,135). The various methods for establishment of geoidal profiles and the associated problems are discussed in Section 3.

5.2.4 Gravity Measurements

The application of satellite technology to gravity measurements lies in (1) ship positioning and (2) establishment of gravity base stations. Satellite technology has already contributed significantly to the determ-

ination of the gravity potential coefficients and to large scale variations in the gravity field. It is expected that satellite altimetry will contribute indirectly to determination of intermediate wavelength variations in the gravity field (11,85,86,94,112,152).

Gravity measurements in various parts of the world are made by many government agencies and private organizations. Gravity is important in geodesy for determination of the figure of the earth and in satellite-orbit determination. Gravity anomalies influence the accuracy of inertial navigation systems (36,106,117). Gravity measurements are also made in support of geophysical exploration for mineral resources development(14,15,123). To realize the full potential of gravity for geodetic and geophysical applications, a measurement accuracy of better than 0.1 mgal is required. The largest gaps in the measurement of the gravity field are over ocean areas. A $\pm$1-mgal accuracy in gravity measurements over the oceans will contribute significantly to achieving most of the geodetic and ocean-ographic requirements. With better than 1-mgal accuracy at sea, many more scientific and economic problems can be solved. To achieve 1-mgal accuracy at sea will require improved positional accuracy and the establishment of base stations at sea. From the point of view of marine geodesy, control points could be established and used as gravity base stations. The largest errors occurring in gravity measurement at sea from both shipborne and airborne instruments are attributed to errors in navigation and particularly to inaccurate knowledge of ship velocity. The 1-mgal accuracy implies knowledge of ship velocity to an accuracy of about $\pm$5 cm/sec. Improved accuracy in continuous geodetic positions will contribute to improved ship-velocity determination. Although existing satellite positioning accuracy is limited at the present time (conclusive and exact accuracy data based on controlled condition experiments at sea are not available in the open literature), satellite technology has the potential for meeting stringent accuracy requirements provided sufficient resources are available(11,17,25,61,77,110,113,143,152,155,156).

5.3 Environmental Prediction and Ocean Physics

In the oceans, the following environmental phenomena are of
broad significance: earthquakes, ocean currents and circulation, ocean
tides, and sea state. With more understanding of all these it will be
possible, eventually, to anticipate and perhaps control and accurately
predict forces, such as tsunami, that have brought destruction to human
beings, natural formations, and man-made structures throughout the world.
Such knowledge will make commerce and resource development safer and more
economical, enhance man's ability to control pollution and to dispose of
wastes effectively, and promote national defense and related national
interests. Ocean farming, air/sea interaction, weather prediction, and
search and rescue operations will also benefit, as will every other
activity conducted in the oceans(2,3,4,15,18,20,25,28,143,151).

The potential of marine geodesy for environmental prediction
and preservation has not been fully developed. As shown in Section 4.1,
the few marine geodetic experiments conducted to date have concentrated
on application of existing geodetic techniques and development of new ones
for solution of the problem of relating a ship's surface position to
ocean-bottom transponders(60,111,115,119). However, the accuracy achieved in
one of these experiments shows the potential for application of marine
geodesy to ocean physics problems. For example, the use of geodetic and
statistical software techniques with different sets of refraction-corrected
acoustic slant ranges from three ocean-bottom transponders resulted in
recovering the mean height of the ship to $\pm$1-meter standard deviation in
5000-m water depths(116). Figure 5.1 shows the resultant histogram and one
sigma normal curve as an indication of the precision obtained in the
Bahamas experiment. Such results show high potential of geodetic control
for use in solving ocean-physics problems as well as providing accurate
ground truth.
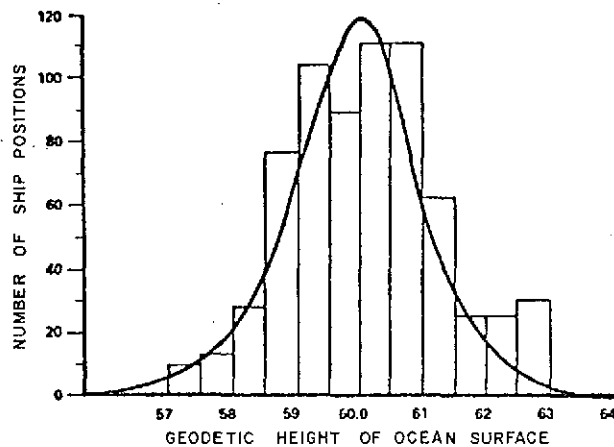
FIGURE 5.1 PRECISION INDICATION OF OCEAN-HEIGHT DETERMINATION

Accordingly, satellite technology can contribute to solutions of ocean environmental problems such as sea state, ocean tides, mean sea level, sea-floor spreading, and ice-sheet motion, which are discussed below.

5.3.1 Sea-State Determination by Geodetic Acoustic Techniques

The application of marine geodesy to sea-state determination is related primarily to the use of the control point in determining the height of ocean waves. This is done in terms of measurements of the two-way travel time of acoustic signals transmitted from surface equipment to ocean-bottom acoustic transponders. Changing sea-state conditions cause the height of a buoy, or platform, on the ocean surface to vary with time relative to the ocean bottom. Figure 5.2 shows how, by analytical processing of the intersection of acoustic slant ranges from at least three geodetically

located ocean-bottom transponders, it would be possible to establish the
surface topography of that portion of the ocean, as a function of time to
an accuracy of about 30 centimeters.
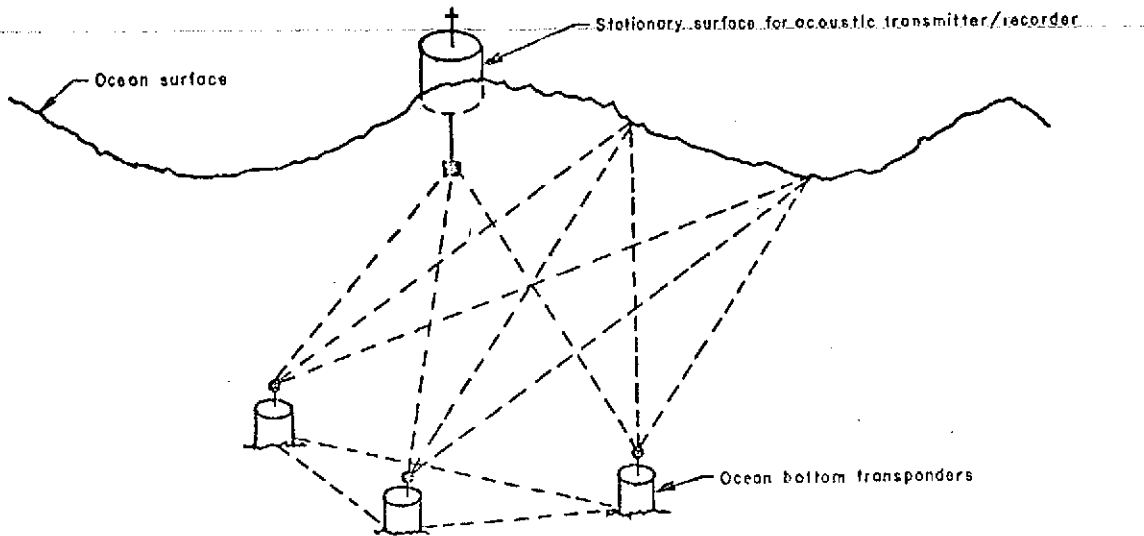
FIGURE 5.2   DETERMINATION OF OCEAN-WAVE HEIGHT BY INTERSECTION OF
ACOUSTIC SLANT RANGES FROM OCEAN-BOTTOM TRANSPONDERS
TO "STATIONARY" BUOY ON OCEAN SURFACE

It is essential that the acoustic interrogator in the buoy be
operated at variable repetition rates so that range samples representative
of the entire spectrum of wave periods of interest can be obtained. The
important parameters to be determined are the differences in height between
the wave crests and troughs. It is interesting to note that the effect of
systematic errors due to inaccuracies in the system delays and acoustic
velocity of water cancel out. The horizontal components of the buoy's
motion and the finite speed of underwater sound may cause some difficulties
and need further investigation. The application of geodetic adjustment
techniques to the data should alleviate some of these difficulties. For
example, Figure 5.3 shows a cross section of the actual wave-length curve
(A) and the deduced curve (B) resulting from the intersection of acoustic

slant ranges. Analytical studies indicate that within the limits of experimental error, the two curves should have identical wavelengths but different amplitudes. The deduced amplitude will always be smaller than the true one.

FIGURE 5.3   COMPARATIVE WAVE PATTERNS

Analytical and statistical procedures to determine true amplitudes are under investigation at Battelle, and thus this problem can be alleviated.

Another new technique for measurement of sea state (wave heights and directions) by bistatic electromagnetic Bragg scatter is being developed at Battelle for NASA(128). The technique involves the use of an HF transmitter mounted on a ship or buoy, and an antenna and receiver mounted on the satellite. Sea state is measured by comparing, in the spacecraft, the transmitted and scattered signals from the ocean surface. It is planned that the device will be used first in an aircraft/buoy configuration to simulate the satellite case. If the experiment is successful, the technique will then be recommended for future satellite applications. In the mean time, the device should be uniquely useful in the aircraft/buoy mode for the collection of ground truth sea state information in support of planned altimeter satellite missions. In addition to being required for satellite altimeter data verification and use, sea-state measurements are required for ocean-dynamics studies, global meteorology and air/sea interaction, and marine geodetic investigations (21,32,140,150,151).

5.3.2   Open-Ocean Tides Measurement, and Mean-Sea-Level Determination

The application of a new independent approach to measurement of ocean wave heights and tides by geodetic acoustic techniques offers another potential for application of marine geodesy and satellite technology to ocean physics problems (60,116,119). Such a "tide-gage" operated for an

extended period will furnish data for the determination of mean sea level at various control points. Such data can be correlated with satellite altimetry data in the same area to define an absolute geoid and to furnish calibration points for tidal determination from satellite altimetry.

The exact magnitude of ocean tides is not known at the present time. Because ocean tides exert a loading effect on the solid earth, their separation from earth tides is of great importance for obtaining accurate information on the earth's interior(13,18,120). Progress is being made by NOAA on measurement of ocean tides using ocean-bottom pressure transducers.

The suggested geodetic approach involves installation of specially designed and calibrated ocean-bottom-mounted transponders and buoys moored over the transponders in suitable areas of the ocean. Perhaps the same test area where NOAA is planning to demonstrate tsunami-prediction capability, using pressure transducers, buoys, and satellites, could also be used to demonstrate this tides-measurement approach. The buoys would be equipped with acoustic transmitters and receivers to continuously or periodically (at specific intervals) measure total travel time to the transponders, as shown in Figure 5.2. In addition, the buoys would be equipped with radio transmitters to relay the acoustic travel times to the satellite, which in turn would relay them to a computing center. The buoys and transponders could be spaced so that any wave buildup, such as a swell due to tsunami buildup, could be detected and warnings immediately released. The use of a geostationary satellite is ideal for tsunami detection since one satellite, for example, would be sufficient for covering the whole Pacific Ocean. Figure 5.4 shows a schematic of ocean surface waves superimposed on a mean tidal curve. Owing to sea-state and residual measurement errors, a plot of such height data as a function of time would exhibit irregular wavy scatter around a sinusoidal curve depicting ocean tides. The tide curve can be derived graphically or analytically. From prolonged determination of ocean tides at the control points, the applicability of the method for determining mean sea level in the area can be demonstrated experimentally. The advantage of this method, of course, is that if affords measurement of ocean tides (same as by coastal tide gages) without masking them with earth tides.
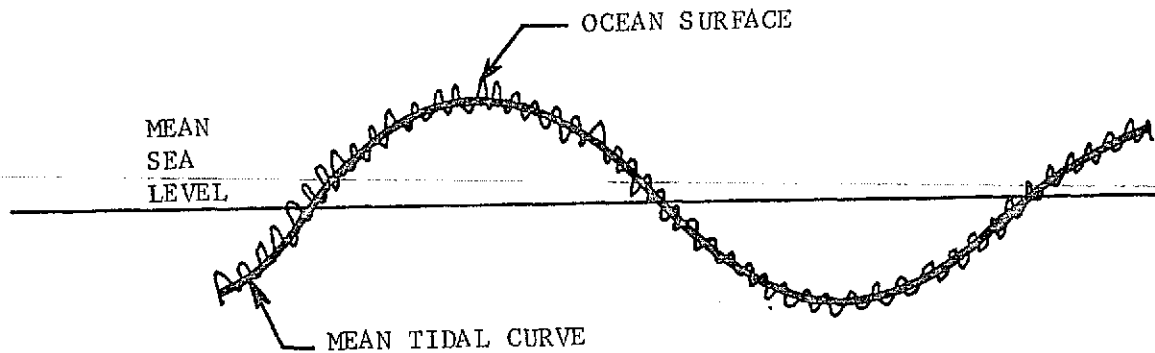
FIGURE 5.4   OPEN-OCEAN TIDE AND MEAN-SEA-LEVEL DETERMINATION

The planned NOAA stations could become control points, and geodetic acoustic techniques could provide a means for comparison and evaluation of NOAA's current and planned tsunami-prediction-system capability. The National Data Buoy Program expects to deploy many buoys by the end of this decade; the International Decade of Ocean Exploration will also, no doubt, have similar data-collection programs, involving buoys, which eventually could be used in the proposed program(18,79). Obviously international cooperation would be easily obtained in such a program since tsunamis are not confined to national boundaries(70).

5.3.3   Glacier and Ice Sheets Motion

In a previous ad hoc study to NASA (17) on potential applications of satellite geodetic techniques to geosciences, it was revealed that satellites offer a potentially powerful tool for monitoring glacier- and ice-sheets growth and velocity of flow. The effect of climatic changes on glacier growth and motion is not well understood. Also, it was indicated that knowledge of the ice motion in Antarctica and Greenland is important to the accurate determination of existing mass balance of the ice sheets. Exact determination of this mass balance is significant as a climatic indicator and as an important boundary condition on attempts to explain the apparent eustatic rise in sea level taking place at the present time. The horizontal motion of these ice sheets is estimated at 10 to 100 m/year,

and that of glaciers is in the range of 100 to 1000 m/year. Horizontal
accuracies of 1 and 5 meters, respectively, were recommended as required
for obtaining best results. Such stringent accuracy requirements place
a great demand on both ground and satellite geodesy techniques. Again, the
application of geodetic acoustic techniques using marine control points
and satellites as a relay offers the best potential for monitoring such
motions. The detection of the $\pm$1-m horizontal motion can be achieved
easily, relative to the control point on the bottom, thus offering the
most efficient and accurate means of determination. An array of ocean-
bottom transponders could probably be quite accurately surveyed and
calibrated from surface ice by conventional geodetic traverse surveys.
Specially designed equipment to withstand the arctic environment will
be required and should not be too difficult to develop.

5.4 Geology, Geophysics, and Resources Development

Successful and economic exploitation of ocean resources requires
that accurate maps and charts be available and detailed surveys be made.
Marine geodesy and satellite positioning capability are shown in
Section 5.2.1 to provide the basic information for meeting such require-
ments. The various activities involved in the development of ocean
resources include all types of geophysical and geological surveys, dril-
ling, production platforms, surveys by ships, and pipeline laying. The
relevancy of marine geodesy and the associated application of satellite
technology to the development of resources are discussed below.

5.4.1 Geology and Geophysical Explorations

The potential applications of marine geodesy and satellite technology
to geological and geophysical explorations of the oceans lie in (1) precise
ship position determination and (2) use of the geodetic control for base
stations and for detailed surveys. Doppler satellite navigation already
provides ship positional accuracy to about 200 meters. Satellites offer an
important advantage in that they have worldwide-coverage possibility.
Improved accuracy in satellite ship positions will be required for detailed
surveys. The use of geodetic control will improve accuracy and allow return

to the same stations at a later time. The control points can serve as base stations for making gravity measurements to determine absolute gravity for geodetic purposes and to make instrument drift corrections. Control points will permit investigations of secular variations of the magnetic field. Detailed geophysical measurements in the vicinity of the control points will provide "ground truth" for airborne measurements. The location of drilling rigs which requires an accuracy of a few meters can be achieved with reliable geodetic control (1,2,6,7,9,11,13,20,47,78).

A matter related to horizontal positioning at sea is that of knowing positions of data obtained from remote measurements and by remote sensing methods. When a ship is conducting a survey or is towing a submerged or surface sensor platform, as is the case in seismic and magnetic and oceanographic surveys, the ability to relate the position of the sensor and the data generated to the ship's position bears directly on the integrity of the resultant maps and charts. As more detailed surveys become required, the position accuracy requirements increase.

Marine surveys are normally positioned by shore-based electronic systems, but satellites are being looked upon with increasing interest and anticipation. Multiple systems are also used. The choice of the system for use depends upon availability, distance-from-shore, accuracy, and purpose of surveys. Whatever the system used, the purpose is to extend horizontal control into marine areas. The control may be based on various datums. All positioning systems have strengths and limitations. A shore-based system's strongest capability is close to shore. In the deep ocean, no suitable surface-based system exists for geodetic measurements. Satellites' strongest capability is extended coverage (worldwide), and in certain applications could be most accurate if used with geodetic control . Several oil and geophysical companies already use Doppler satellite navigation equipment for positioning their survey ships and drilling platform locations (18,67,74,125,131).

5.4.2 Mineral Resource Development

Economics dictates that the development of natural resources be emphasized in all countries in order to meet future demands posed by increased population and food shortage. Satellite geodesy, as a tool to

improve surveying and mapping capabilities, will definitely play a major role in the future exploitation of natural resources, particularly those in the ocean and other remote areas of the world.

The report of the United Nations on "Mineral Resources of the Sea" (15) includes detailed descriptions of problem areas wherein both marine geodesy and satellite technology can help provide solutions, for example,

(1) Mineral exploration and evaluation techniques including survey-platform and position-fixing methods, bathymetric and topographic surveys, geological prospecting, geophysical prospecting, and geochemical prospecting.

(2) Ocean-mining methods, including production dredging of surface deposits and techniques for exploitation of consolidated subsurface deposits.

(3) Marine mineral development beyond the continental shelves which presents special problems. Solution of these problems will require further scientific and technological research into and promotion of mineral development and jurisdiction.

The most significant contribution that marine geodesy can make to mineral exploration is by developing accurate positioning techniques so that the efficiency of exploration can be increased and its cost decreased. Deep submersibles and satellite navigation, for example, already play important roles in exploration of mineral resources. Accurate position fix is a critical factor in prospecting for undersea minerals, and as the search narrows, so does the degree of error in positioning that can be tolerated. While in broad reconnaissance surveys, an accuracy of 300 meters may be acceptable; 30 meters or less is desirable in more detailed work, and even further reduction to a few meters may be necessary in the delineation of mineral deposits (7,9,77,109). In addition, the establishment of ocean-bottom controls to aid in detailed surveys and to be used as base stations for geological and geophysical prospecting, especially in areas beyond the range of accurate land-based positioning systems, should be among the important geodetic contributions to marine resources development (58,80,108,110).

5.5 International Relationship

Since Geodesy, among other things, deals with the determination of the size and shape of the earth, it is clearly a true international science. The activities of marine geodesy, being of the oceans, likewise contribute to international affairs through establishment of control, boundary delineation, geoid determination, and satellite positioning and measurement capabilities. The establishment of geodetic control points will be an important contribution to international treaties and agreements in boundary determination as discussed in Section 5.2.2. The relevancy of marine geodesy and the requirement for satellite technology are discussed below in terms of national security, commerce, and search and rescue.

5.5.1 National Security

Traditionally, geodesy and, more recently, satellite geodesy continues to make important contributions to national security in several areas, such as the establishment of a unified world geodetic datum, determination of the figure of the earth and its gravity field, and the determination of geodetic positions. While most of the geodetic objectives have been accomplished on land, at least for military operations, those pertaining to marine geodesy are just beginning to evolve. The application of satellite technology to marine geodesy will contribute to national security through the establishment of marine geodetic control; precise ship positioning and velocity determination, surveying and mapping, and geoid determination at sea. Control points and accurate geodetic positions could become of utmost importance, particularly for the undersea long-range missile programs, Polaris, Poseidon, and other advanced weapon systems. If "hard-target" capabilities are required for such systems, marine control points must be accurately established and tied to a world geodetic system as a means for systems accuracy evaluation. NASA's development of precise measurement technology and associated software and hardware capability should be very useful. Accurate ship-velocity-determination techniques are required for use with the Navy Doppler navigation satellite and inertial systems(121). Determination of the geoid and deflection of the vertical at sea are important for their effects on inertial navigation

and missile flight paths, and for establishment of an oceanic geodetic system. Satellites offer the best potential for satisfying marine geodetic requirements of DOD and National Security, from both the points of view of positioning and altimetry. Satellites appear to be the only effective means by which sufficient accuracy can be provided on a worldwide basis for advanced marine weapons systems and antisubmarine warfare(1,9,53,87, 107,112).

5.5.2 Commerce

Contributions of satellite/marine geodesy to commerce are mostly of a potential and indirect nature, involving primarily ship and aircraft positioning and accurate maps. Commerce has a global role, and a worldwide positioning capability is of prime importance for both transportation and safety of navigation. As ship traffic increases, requirements for accuracy in position becomes more stringent. The U.S. Maritime Administration has been given the responsibility and resources to rebuild the U. S. merchant ship fleet to a competitive position. In this connection, satellite positioning information and satellite sea-state-prediction capability will be of great importance.

5.5.3 Search and Rescue and Salvage

Search and rescue operations are among the most vital ocean activities from a priority point of view, especially when human lives are involved or where international politics, national prestige, and security are at stake. Search and rescue operations require the optimum in positional accuracy. Such operations impose stringent demands, particularly in the deep-ocean areas, which can be satisfied only by application of marine geodetic techniques and satellite positioning and communications systems. The establishment of some type of geodetic control forming a local grid will aid tremendously in perfecting search patterns. The speed by which such operations can be initiated and completed is an important factor. An accurate and continuous satellite ship-positioning capability will offer the best advantage. The combination of a satellite system with other systems, such as acoustic and inertial, would relax the continuous positioning requirements.

Retrieval of objects from the ocean floor, whether in rescue operations or for salvage purposes, will have essentially the same stringent positioning requirements. The position accuracy required is dictated not only by surface-position information but also by those relating one vehicle (submersible) or towed instrument to the surface ship. Another factor governing the accuracy is the size of the object and the resolution capability of searching instruments.

5.6 Scientific and Educational Applications

One of the current unanswered scientific questions relates to movement of the continents (continental drift) which is of the order of a few centimeters per year. Detection of such movements will require highly sophisticated measurement techniques and may be accomplished by employing laser ranging and satellite interferometric techniques (17,33,85,91,94). Earthquakes prediction, earth-tidal measurement, and horizontal and vertical movement in the earth structure could also benefit from satellite geodesy techniques if the accuracy in satellite-position determination can be improved by an order of magnitude. Solution of these problems would represent scientific and/or academic breakthroughs. Never before has solid-earth geophysics received such attention and satellite application is becoming more prevalent in the geosciences because it provides a practical means for obtaining data leading to solutions in many problem areas.

Some of the scientific aspects of marine geodesy have been already described relative to its contribution to solution of ocean-physics problems. It was also mentioned that the needed technology, from the point of view of space and marine sciences, has not yet been fully developed or exploited. The growing national and international ocean-oriented interests and activities will force greater emphasis on more precise measurements. Further examples of expected contributions of marine geodesy are herein discussed with respect to (1) figure (size and shape) of the earth, (2) ocean-floor spreading, and (3) ship/satellite tracking and orbit determination.

5.6.1   Figure of the Earth

The capability of satellite technology to accurately locate control points and tie them to various geodetic datums, and also connect islands separated by thousands of miles and determine an absolute global geoid is critically important to geodesy and to the accurate determination of the size and shape of the earth. These are, in turn, important for their contributions to national security, space research, and science and education(43).

Geodesy traditionally has been the only agent for determining the size and shape of the earth and for providing an indirect means of studying the crustal and deeper structure of the earth. The effective exchange of information with other technologies and earth-and-space-oriented sciences has been an important part of this tradition. Marine geodesy is expected to contribute to studies of the figure of the earth by including geoid determination at sea, development of ocean control-point systems tied to national geodetic datums, and geophysical investigations dealing with ocean crustal movements.

5.6.2   Ship/Satellite Tracking and Orbit Determination

Technology developed in the space program can be very advantageously applied to earth and ocean-physics projects; conversely, technology developed in the latter projects can be applied to space exploration. Direct benefits from satellite observations in determining accurate location of tracking stations result in improved satellite orbits and prediction models, reduction in satellite tracking costs from better knowledge of the earth and its gravity field, and reduction in position-fix costs. Further refinements in orbit determination (± 1 m accuracy is immediate goal) require development of sophisticated equipment, techniques, and their applications. These applications can involve utilization, for example, of satellite altimetry, very-long-baseline interferometry, laser ranging, C-band radar, and underwater acoustics. In addition, refinements in the techniques and hardware used in related conventional technology can provide significant advantages in many areas.

Improvement in ground stations positions, measurement precision, and statellite-to-satellite tracking offer potential for meeting this goal particularly where ground tracking stations are available. The establishment of control points at sea in remote areas offers an excellent possibility for improving orbit determination over them. The use of specialized tracking ships such as the Apollo Vanguard, offers great potential. The full potential for utilizing the Vanguard needs to be developed. Tracking capabilities, particularly in the southern hemisphere, are quite limited because of lack of land areas for tracking sites. Ocean platforms positioned relative to marine geodetic control points could provide such tracking capability.

5.6.3 Ocean-Floor Spreading

Advanced satellite techniques using laser or long baseline interferometry, when combined with geodetic acoustic techniques, could make contributions to continental-drift studies and direct measurement of the rate of ocean-floor spreading. The solutions of the problems of continental drift and ocean-floor spreading will contribute to our knowledge of earthquake mechanisms and the formation of the earth's body. The rate of motion of oceanic crust, which has been reported to be of the order of 10 to 17 cm/year, is much larger than the rate of motion of the continents (estimated at about 5 cm/year). Marine geodesy offers a potential for attempts at direct measurements of the motion of oceanic crust. Such attempts would involve employment of interferometric principles and/or laser ranging techniques and a special type of ocean-bottom acoustic transponder to measure and monitor the relative motion of ocean-floor spreading over a period of several years. In this connection, the development of long baseline interferometric techniques using satellites and/or natural sources suitable for geodetic measurements of a few centimeters accuracy should be encouraged (64,104,130). Measurement accuracy of tens of centimeters will still be useful if made over several years. Several experiments for direct continental-drift measurements are being planned. Such experiments should include at least one or two stations over ocean floor areas suspected of crustal motion(91,152). The use of a suitable ship such as the Vanguard has many of the needed measurement systems should also be investigated for this purpose.

5.7 National and International Programs

Many benefits and cost savings can be accrued in various national marine programs if marine geodetic approaches are integrated into the over-all scope of these programs. Contributions are contemplated in environmental prediction, economic resource development, social and legal problems of marine programs. Specific examples of programs that can immediately benefit from certain aspects of marine geodesy that utilize satellite technology are: National Data Buoy Program, National Ocean Surveys, Sea Grant, and Global Atmospheric Research Program.

Marine geodesy can and should play a major role in international marine programs aimed at development of the continental-shelf resources and deep-ocean explorations. The International Decade of Ocean Exploration (IDOE) Program is only one example of many other similar programs in which practically all scientific disciplines except marine geodesy are being represented. The IDOE program (79) is aimed at broad, interdisciplinary, cooperative programs of ocean research and exploration. The Decade is unique in that it recognizes that a major share of world oceanographic effort must be devoted to globally planned and coordinated study of the oceans as a system, for the benefit of mankind. Detailed studies should be initiated to show the interaction of marine geodetic application areas, role of satellite technology, and the benefits from and to national and international programs.

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